Modeling (and observations) of wind turbine wakes

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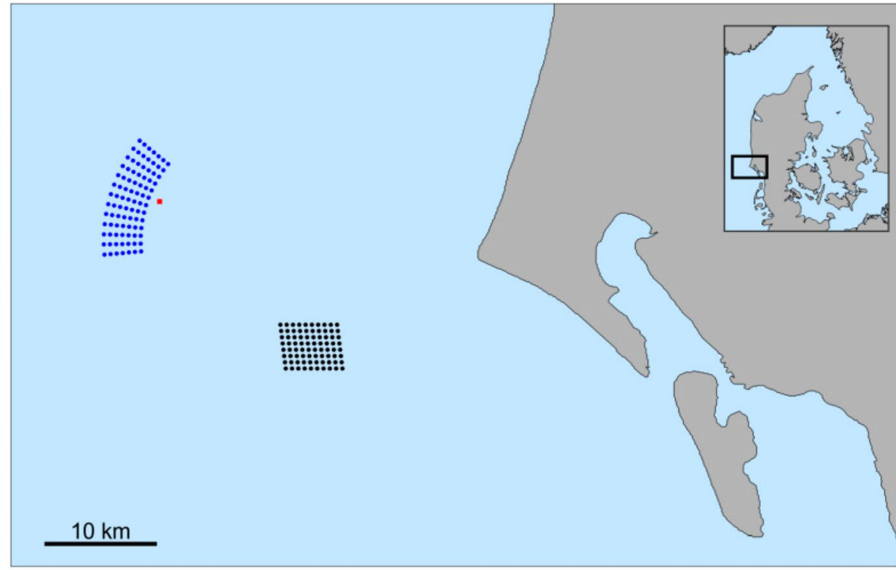
Hydrodynamics modeling and implications for offshore wind development

Wakes are nearly impossible to see

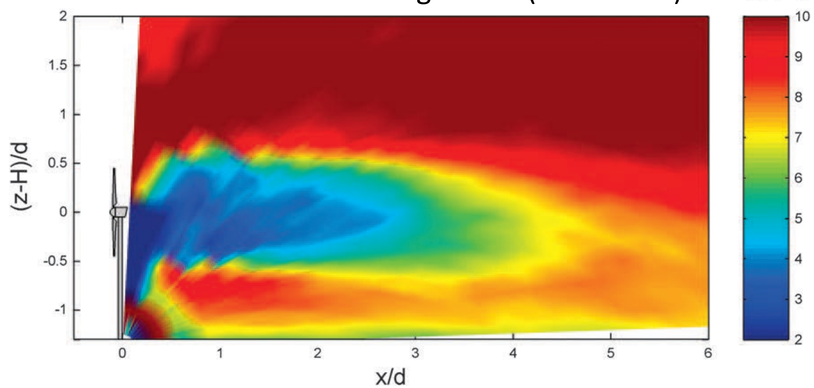

Horns Rev 1 (2/12/2008)

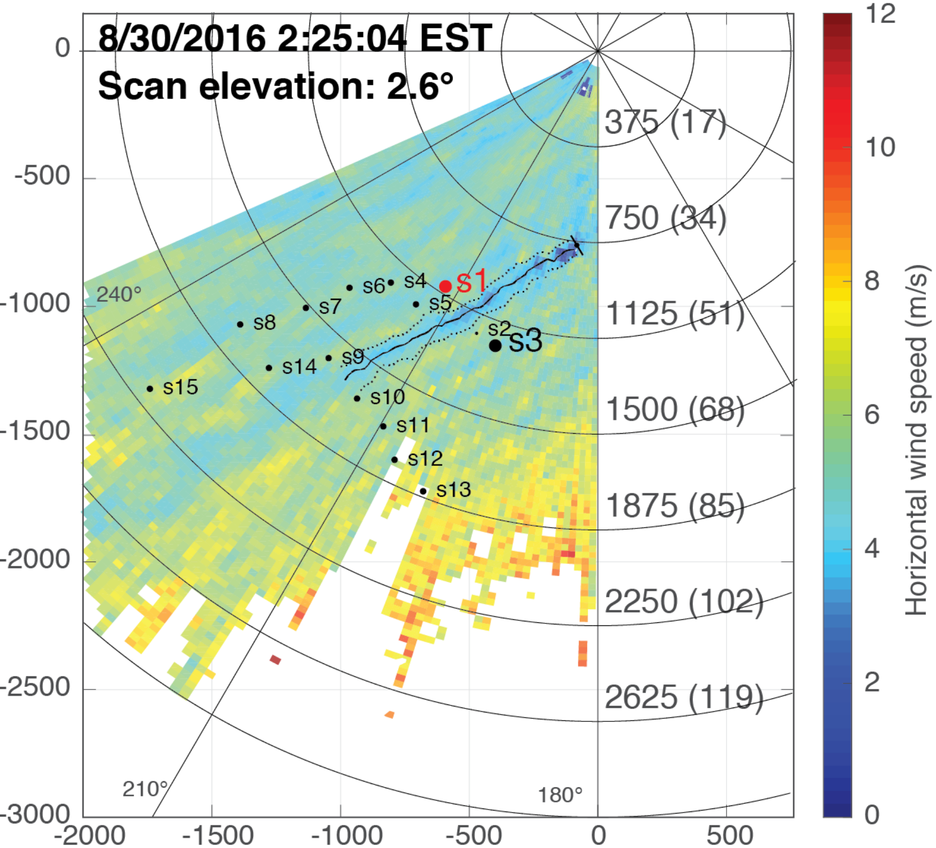


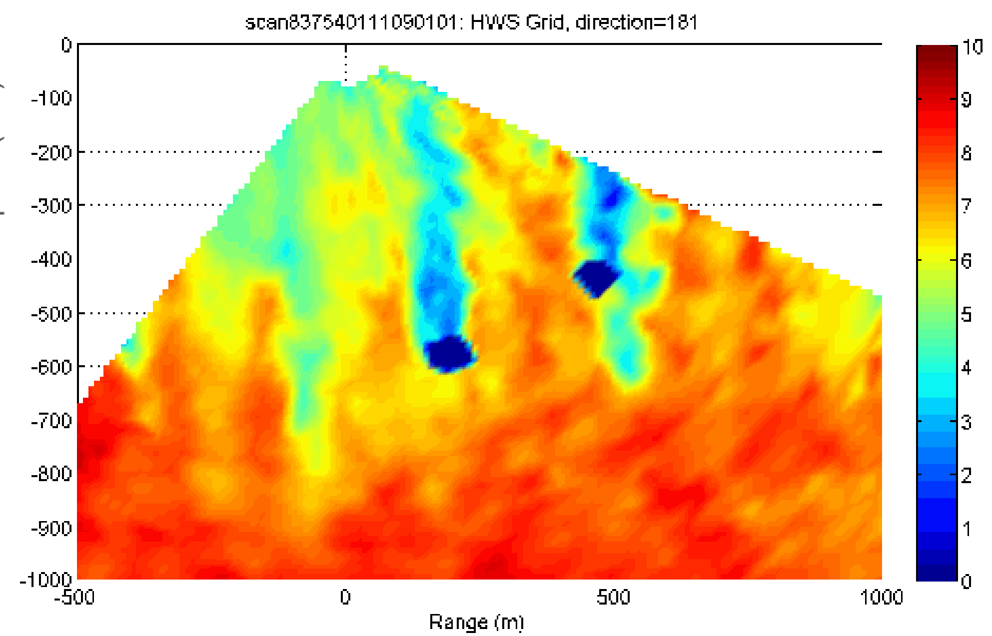

Horns Rev 2 (1/25/2016)

Lidars show wind speed deficit in wakes

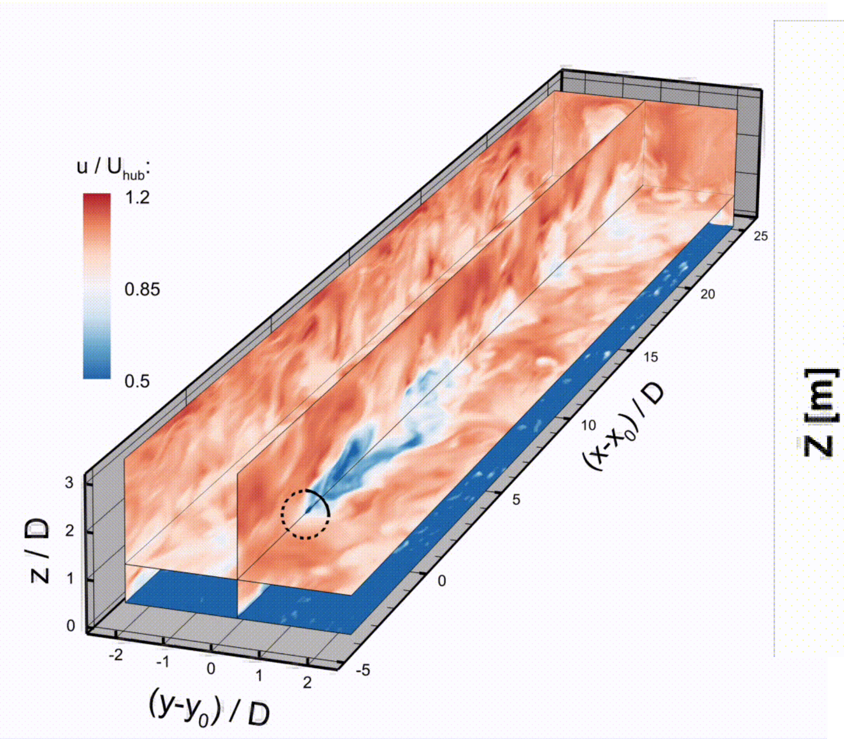
Iungo et al. (JAOT 2013)

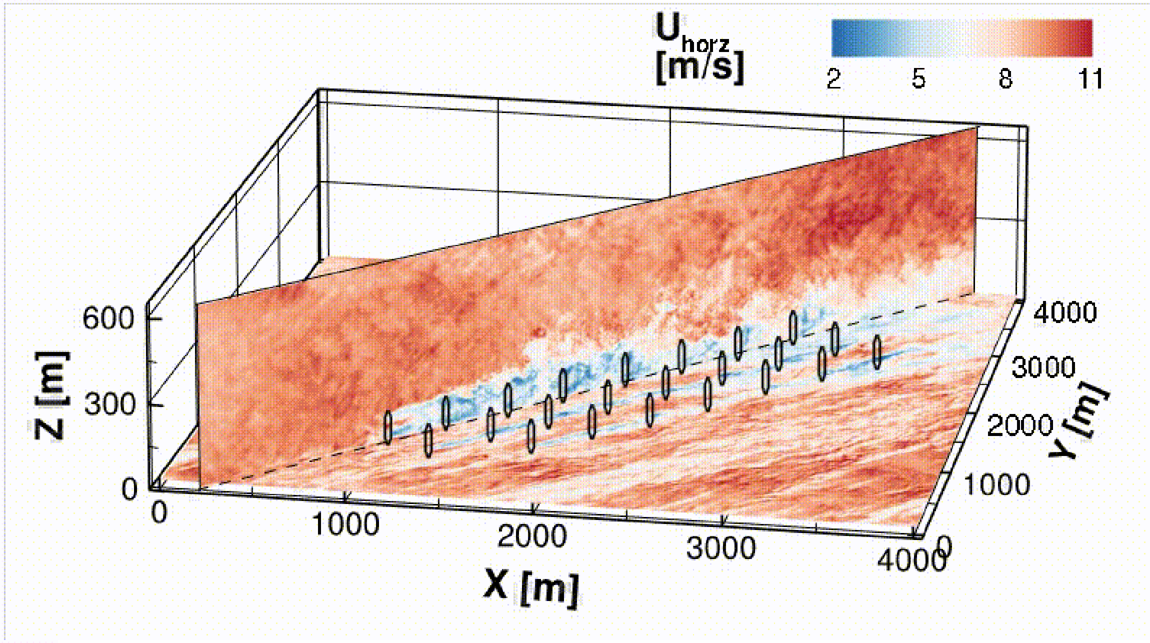






Large-Eddy Simulation (LES) of single- and multi-turbine wakes

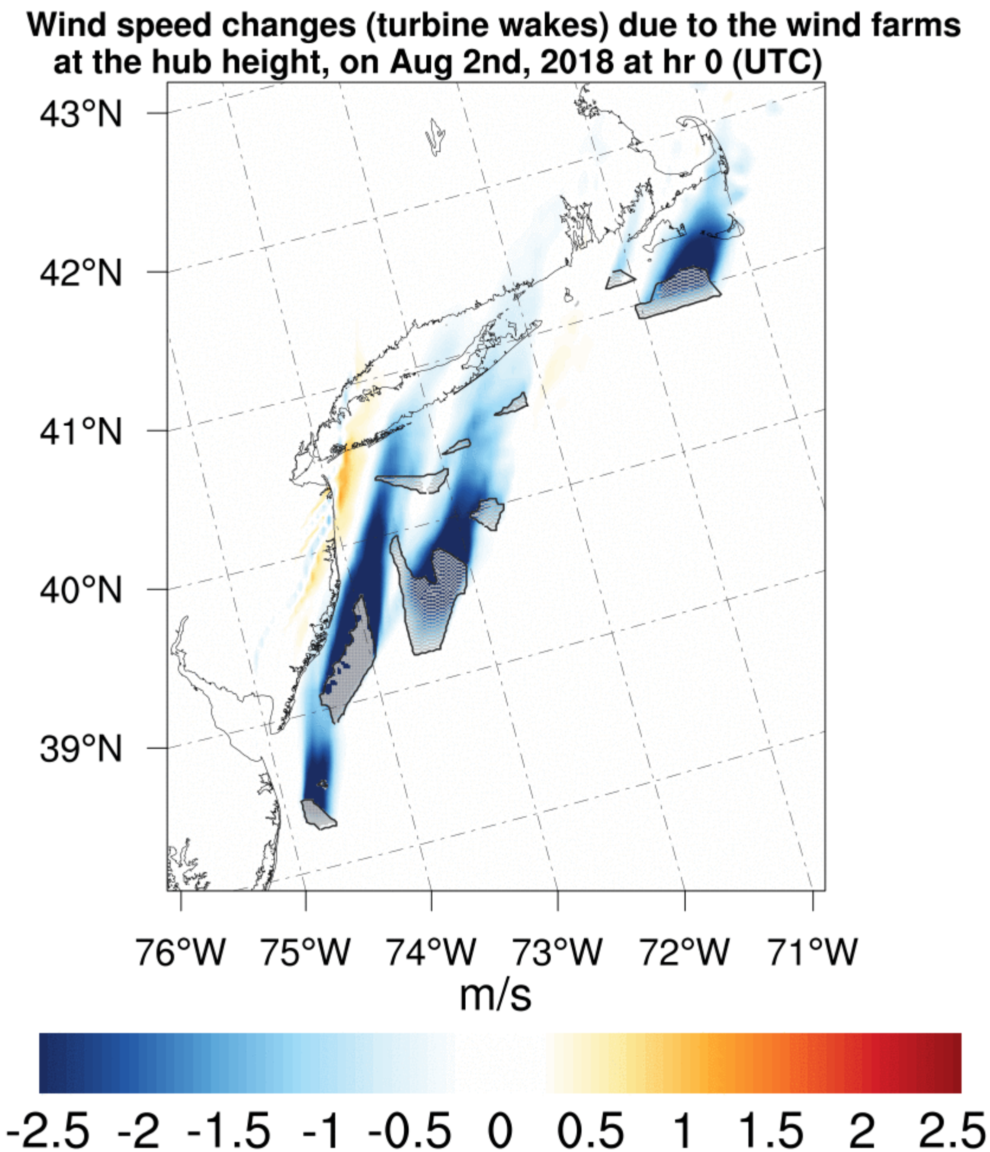




In-house code WiTTS (Wind Turbine and Turbulence Simulator)

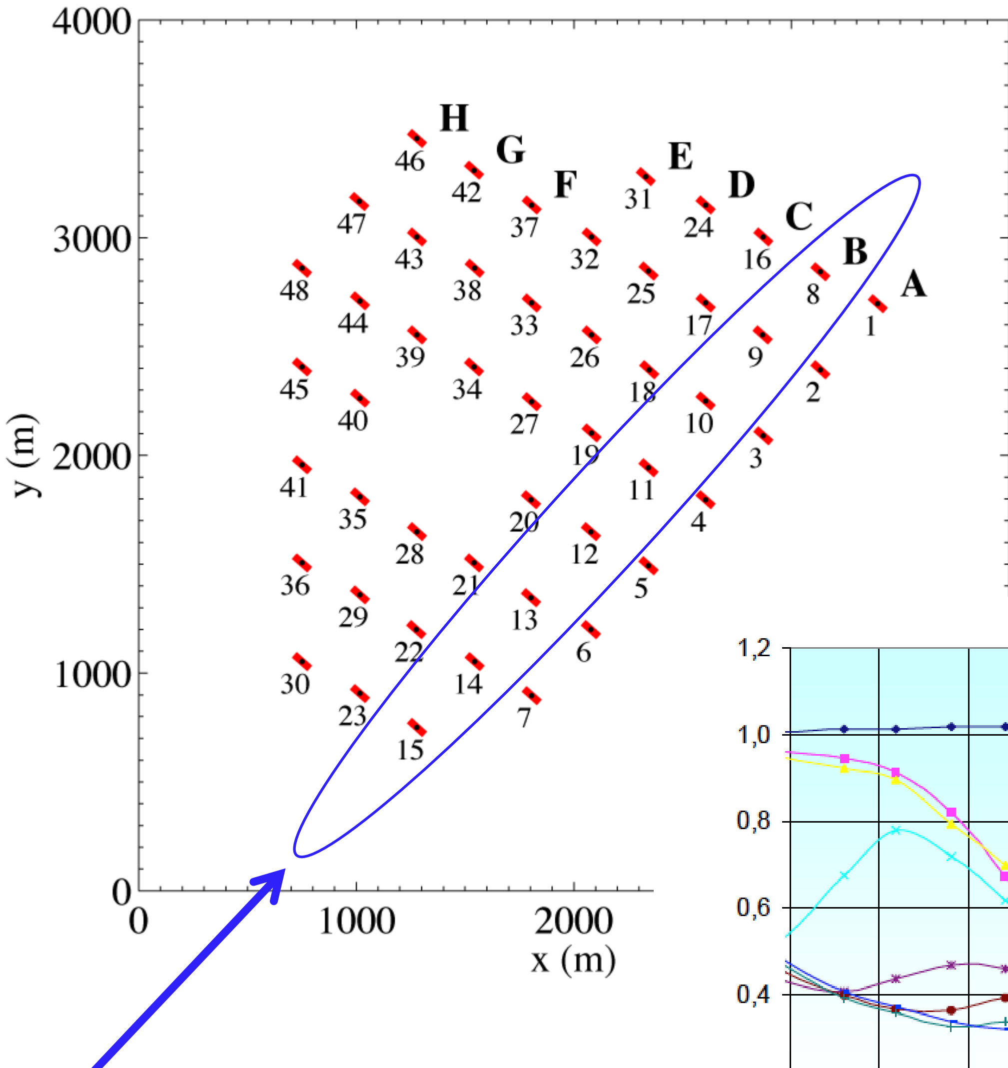
OpenFOAM-based SOWFA (Software for Offshore/onshore Wind Farm Applications)

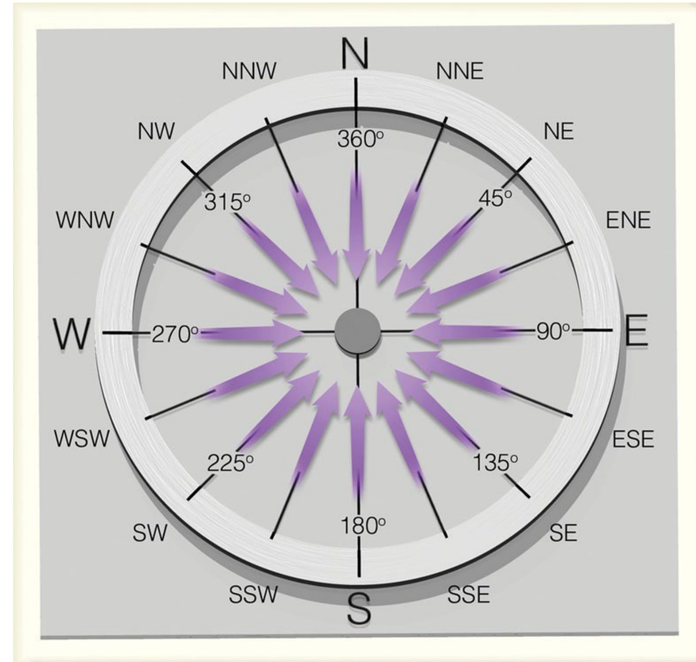
WRF-simulated wind speed deficit

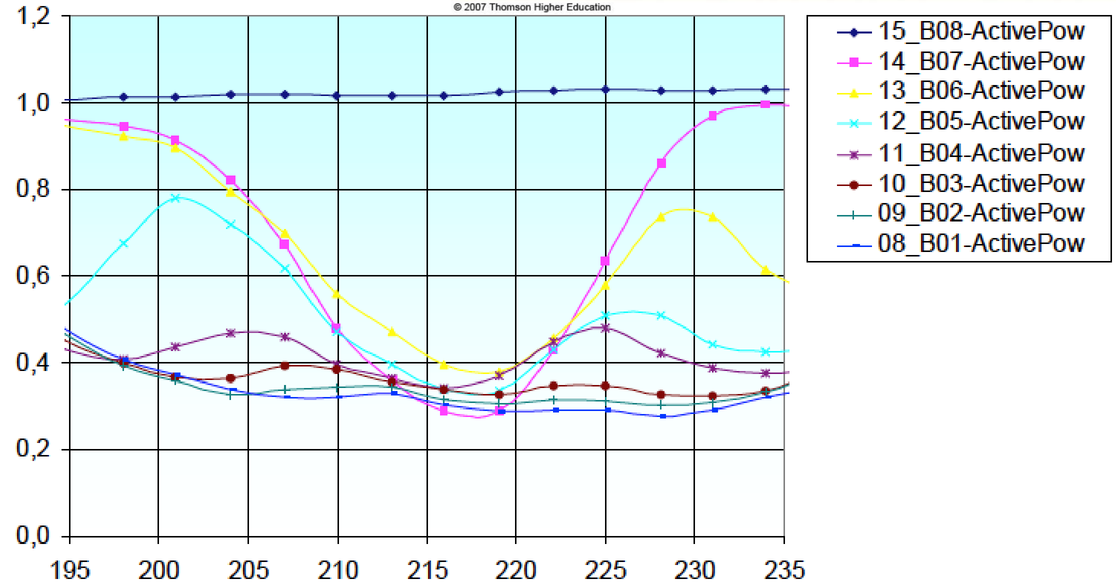


Golbazi et al., 2022

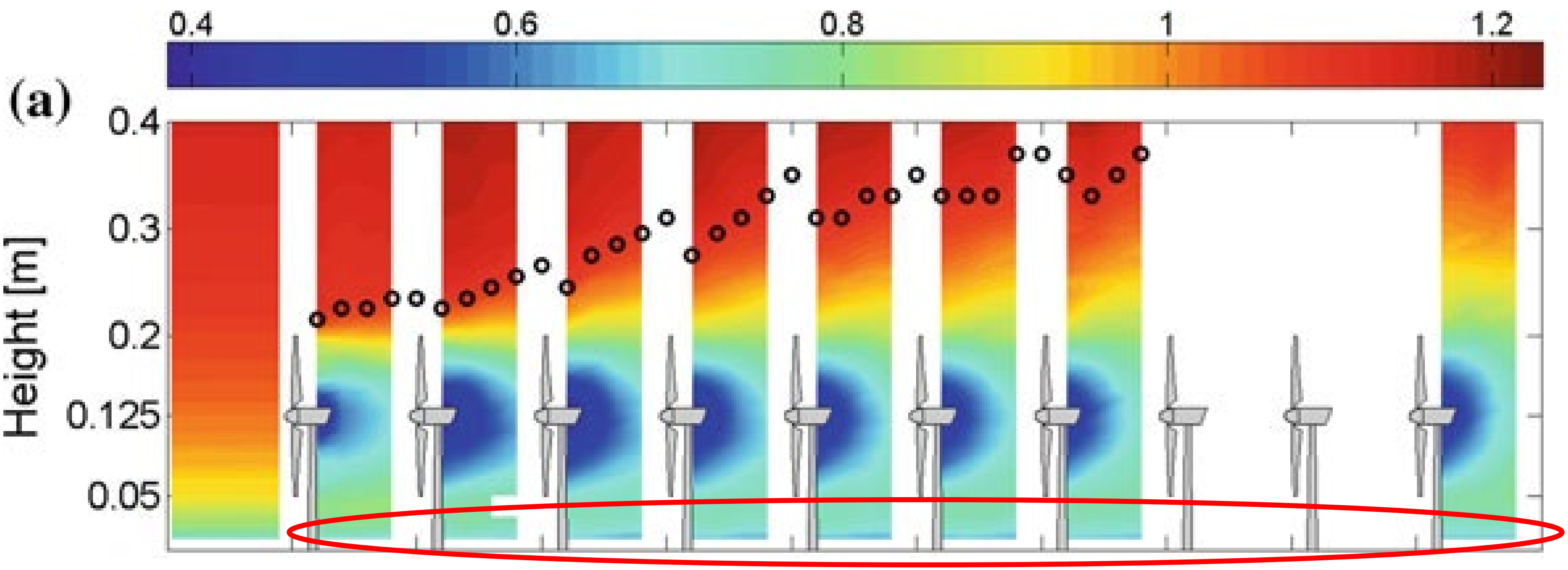
Wind speed deficit = Reduced power







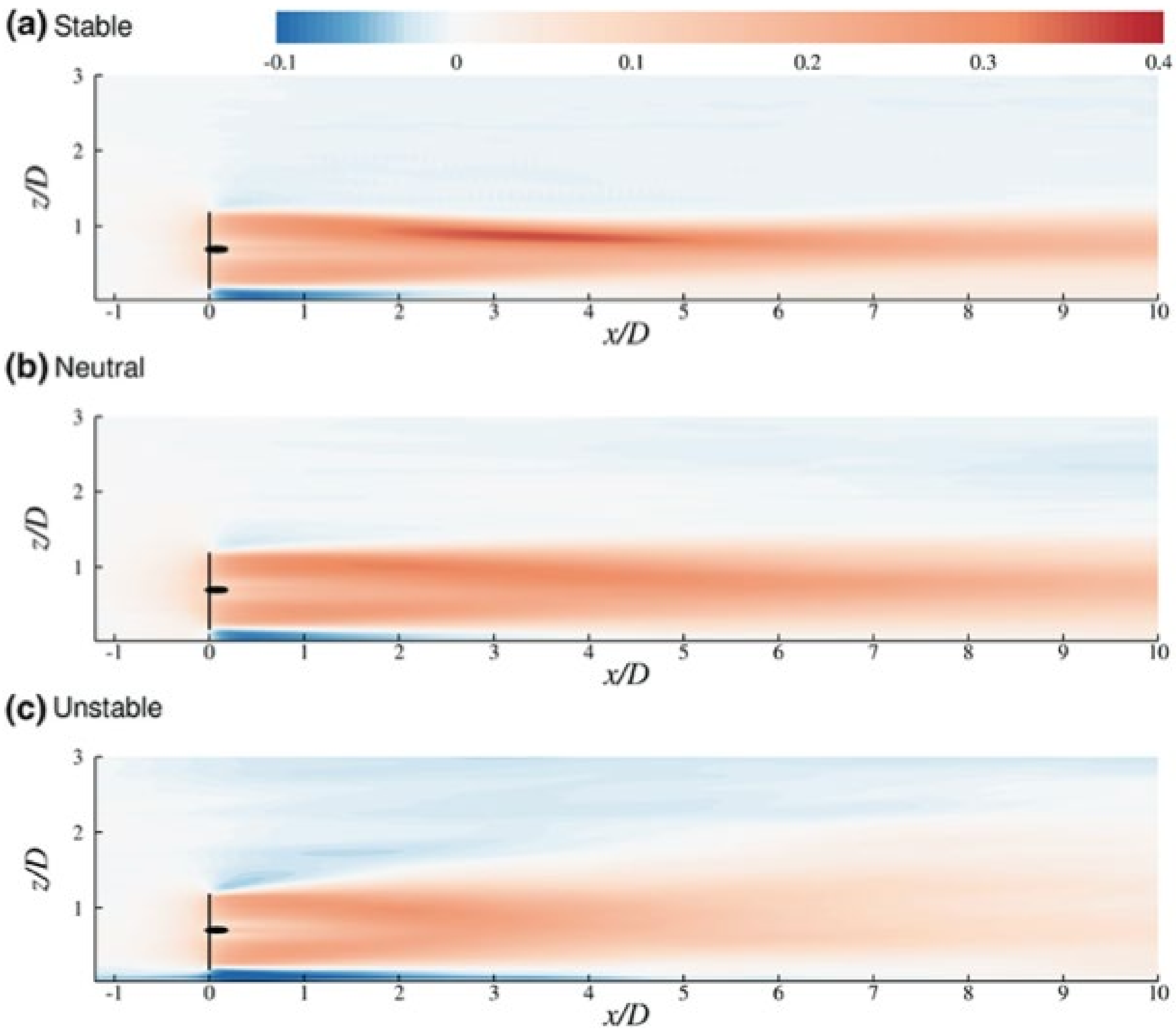
Wind speed deficit: Wind tunnel



Wind speed deficit reaches ground

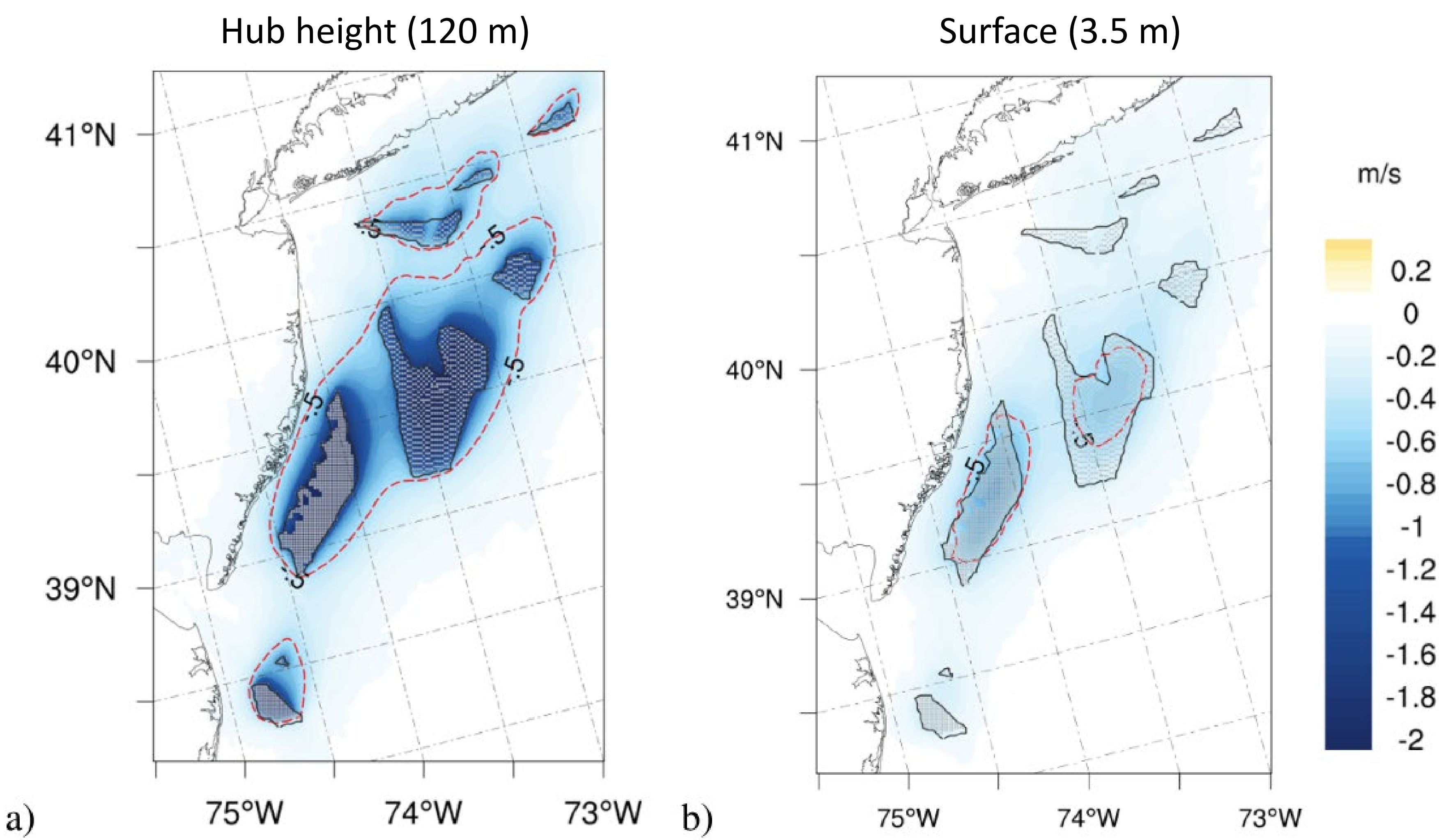
Chamorro and Porté-Agel (2011); Wu and Porté-Agel (2013)

Wind speed deficit: LES



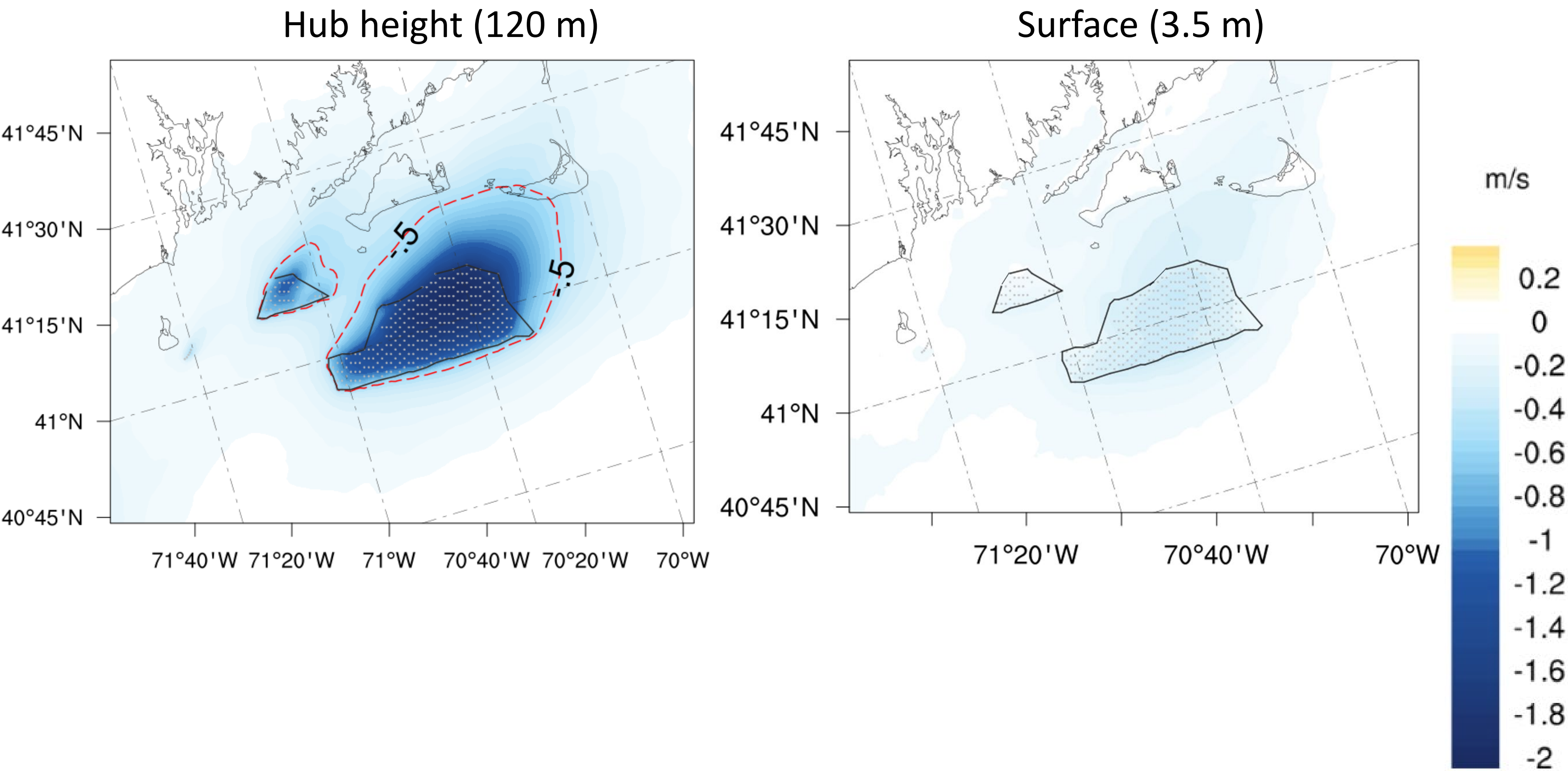
Xie and Archer (2017)

Wind speed deficit: WRF



Golbazi et al., 2022

Wind speed deficit: WRF

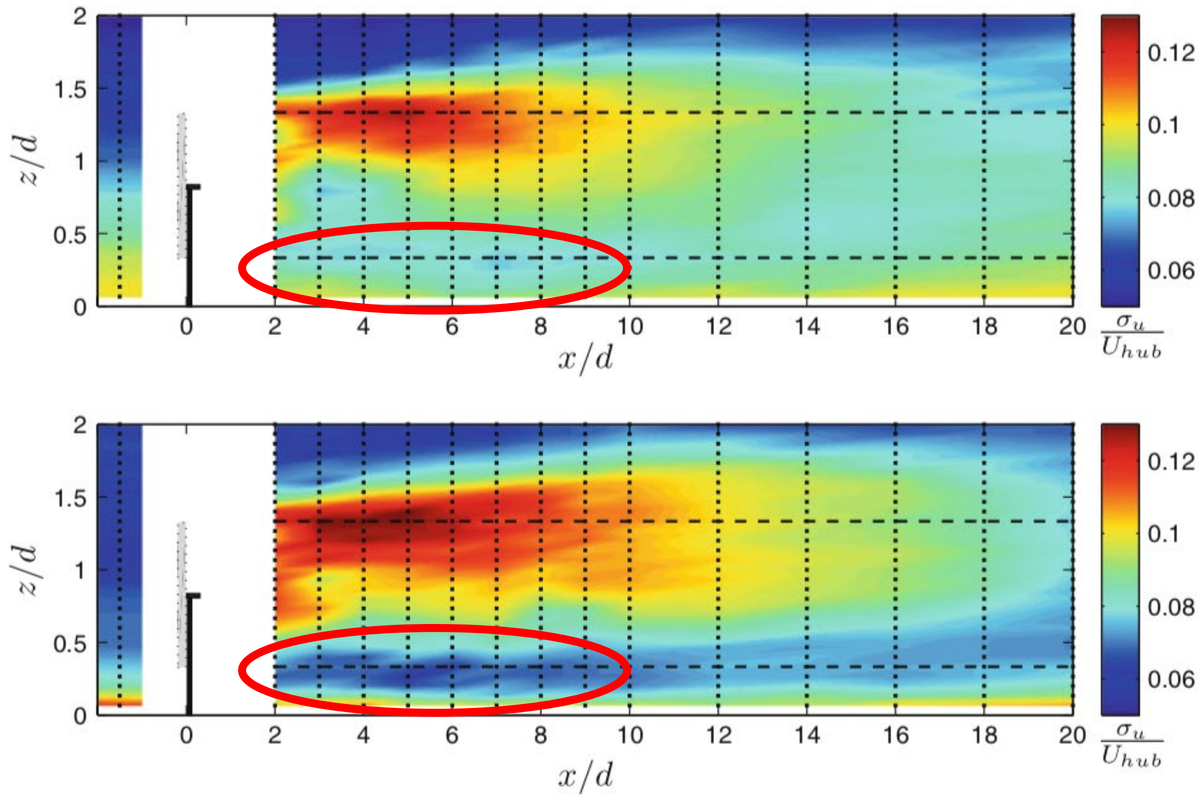


Golbazi et al., 2022

Added turbulence: Wind tunnel experiments

Neutral

Stable



Added turbulence does NOT reach ground

Fig. 7 Turbulence intensity distribution downwind of the turbine at zero span in the neutral (*top*) and in the stable stratified (*bottom*) boundary layer. *Horizontal-dashed lines* represent the turbine bottom and top tip heights and *dots* indicate measurement locations

Chamorro and Porté-Agel, BLM 2010

Added turbulence: More wind tunnel experiments

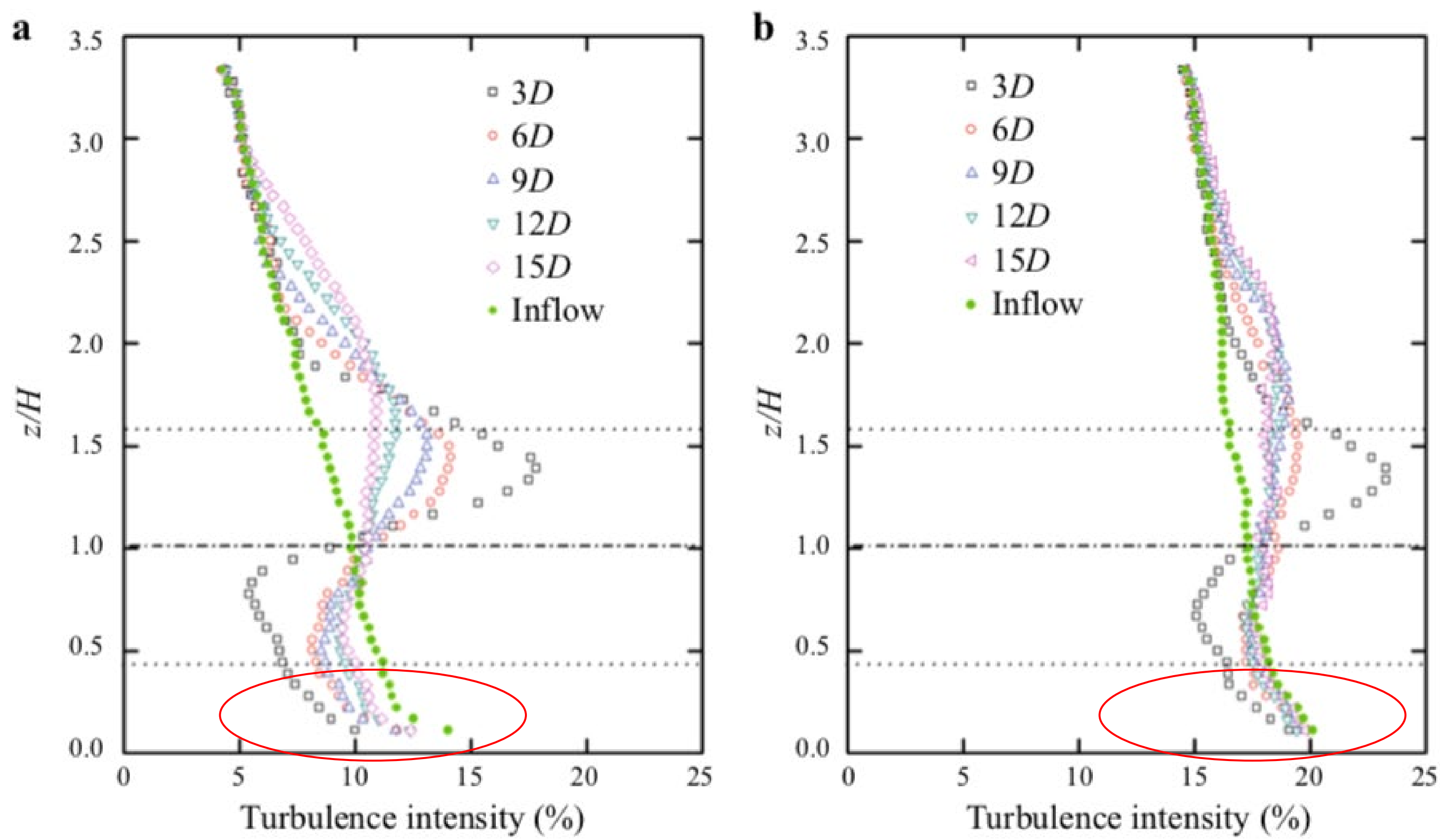
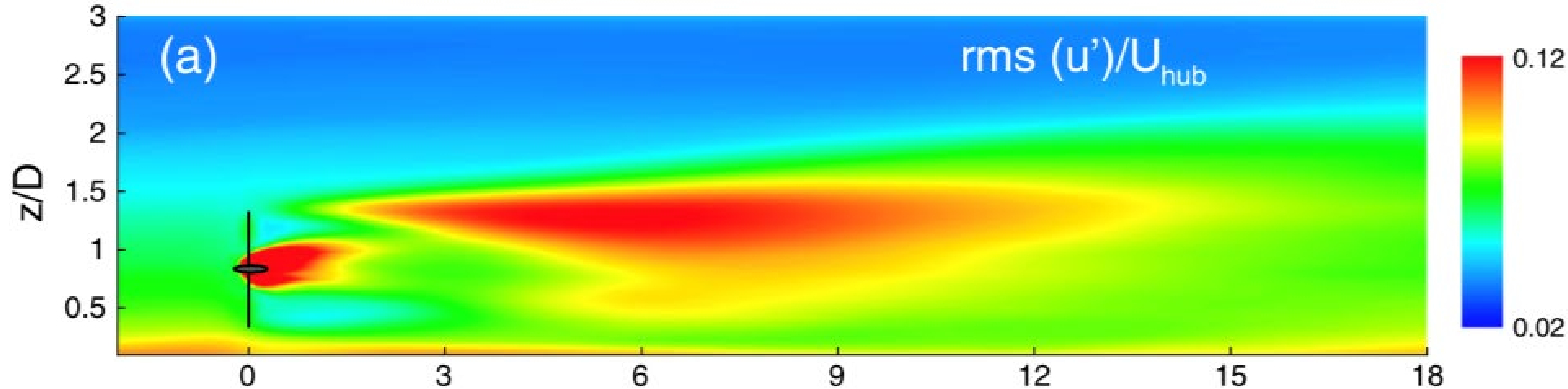


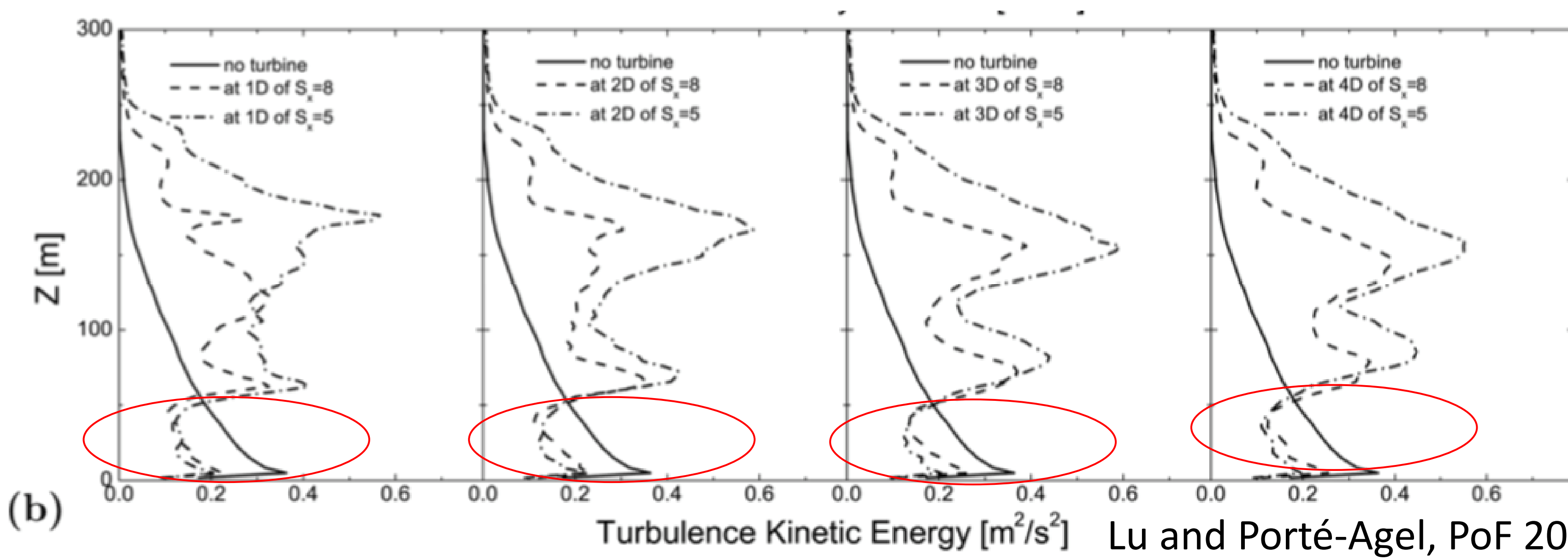
Fig. 8 Measured turbulence intensity profiles at different downstream locations. **a** Low turbulence inflow case; **b** high turbulence inflow case

Tian et al., AMS 2017

Added turbulence: LES

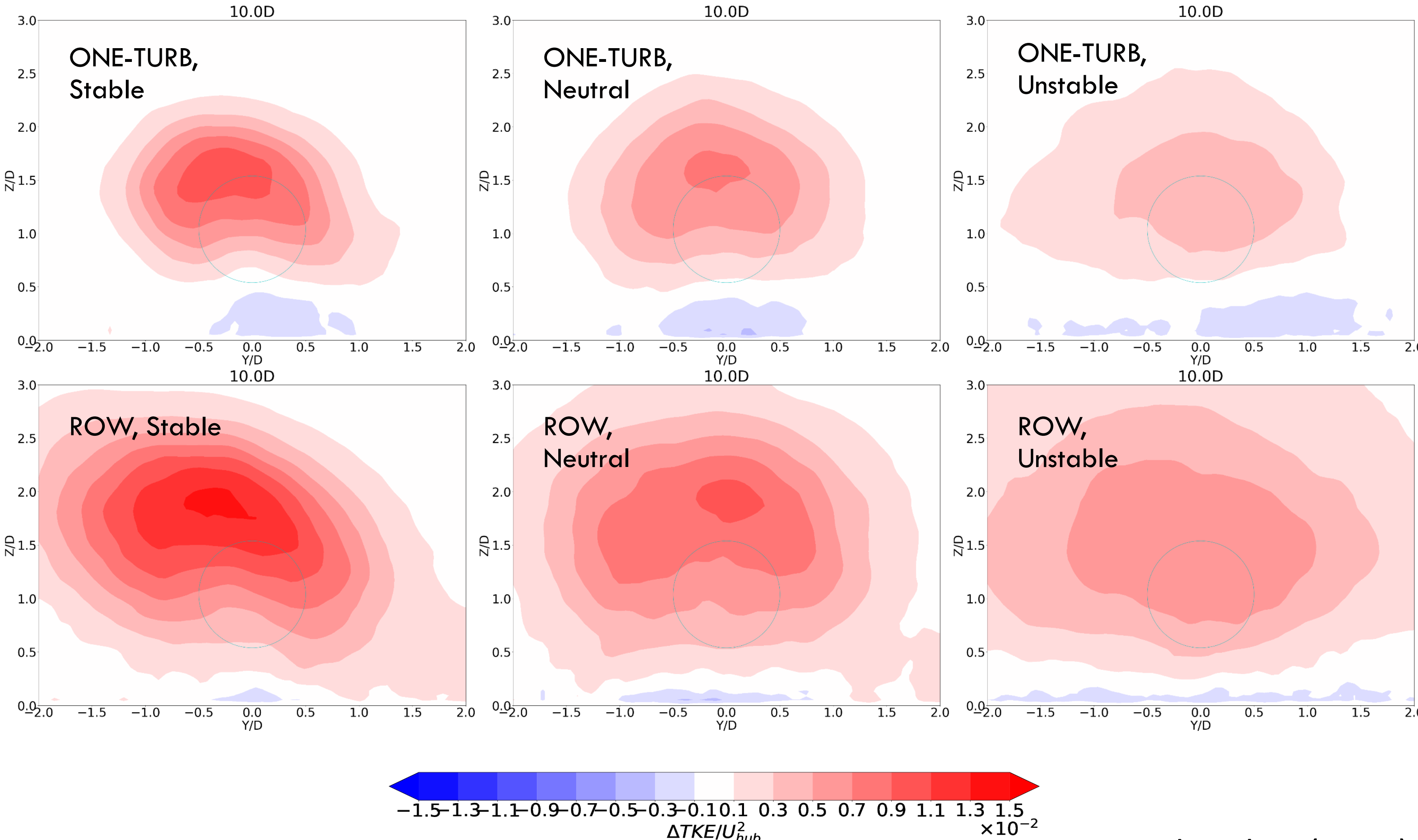


Xie and Archer, WE 2015



Lu and Porté-Agel, PoF 2011

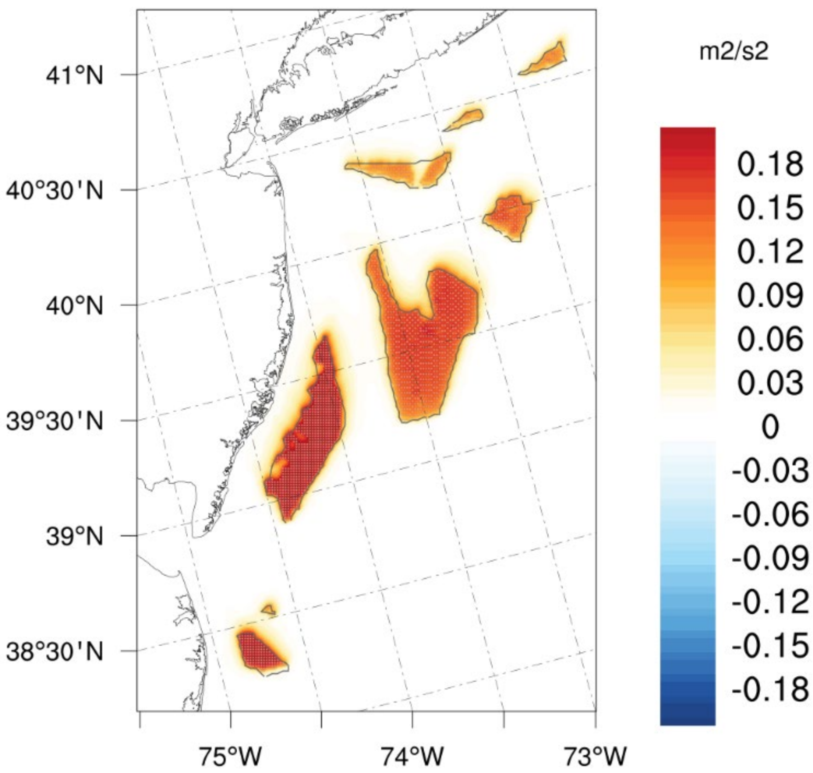
Added TKE: LES



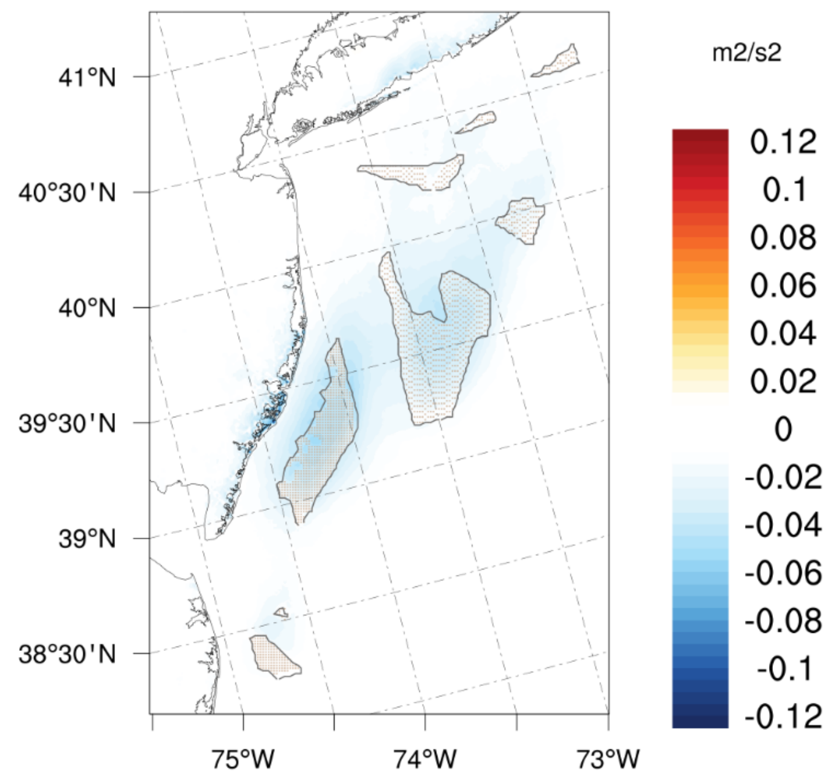
Wu and Archer (2023)

Added TKE: WRF

Near top of the rotor

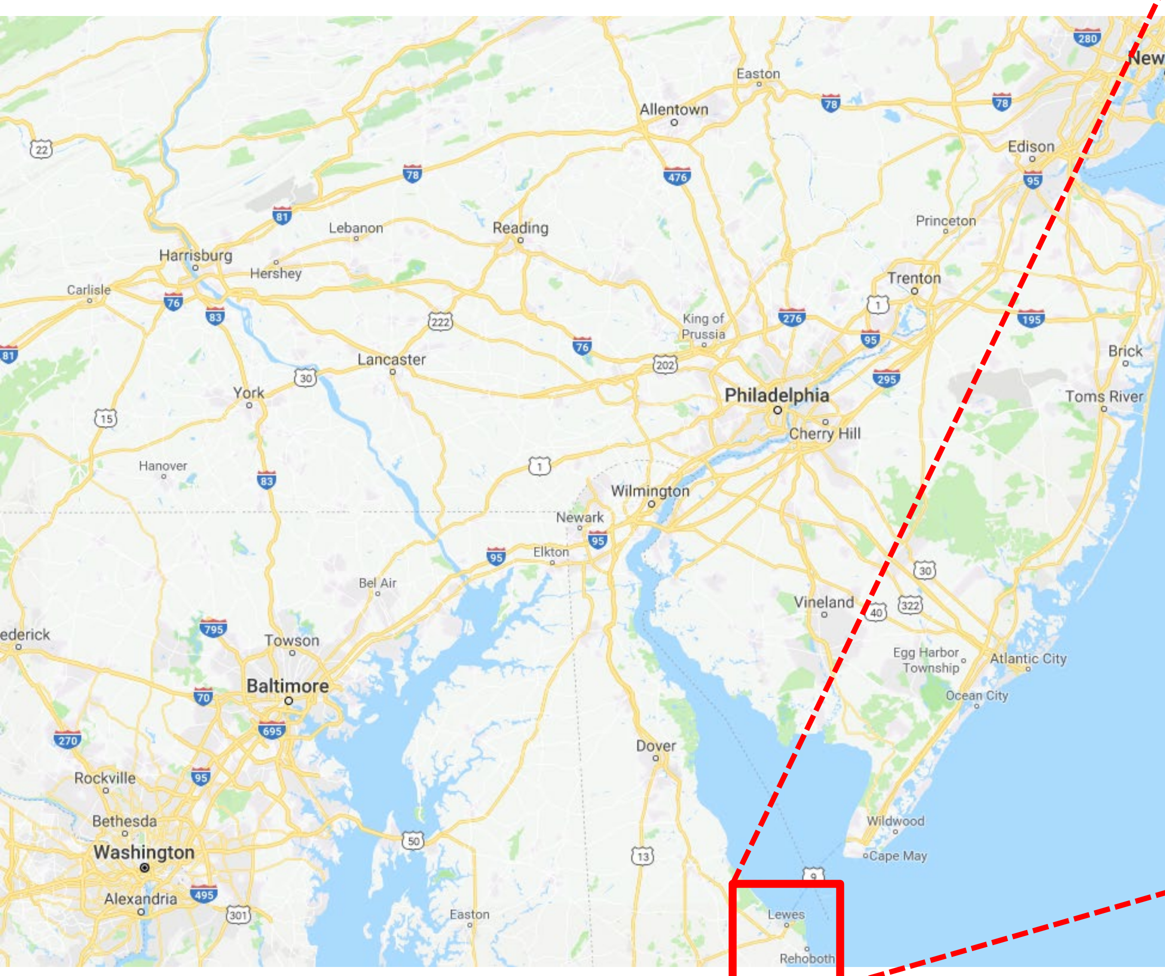


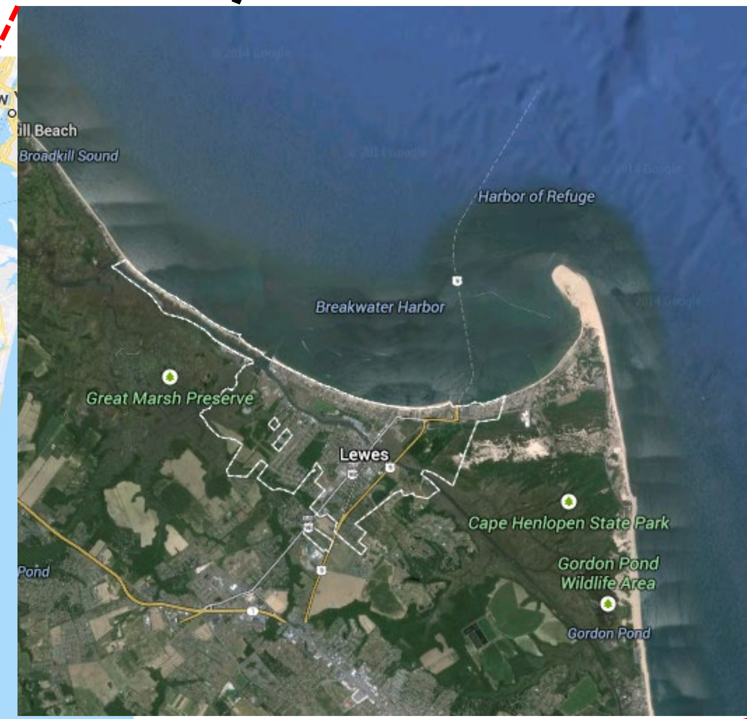
At the surface



Golbazi et al., ERL 2022

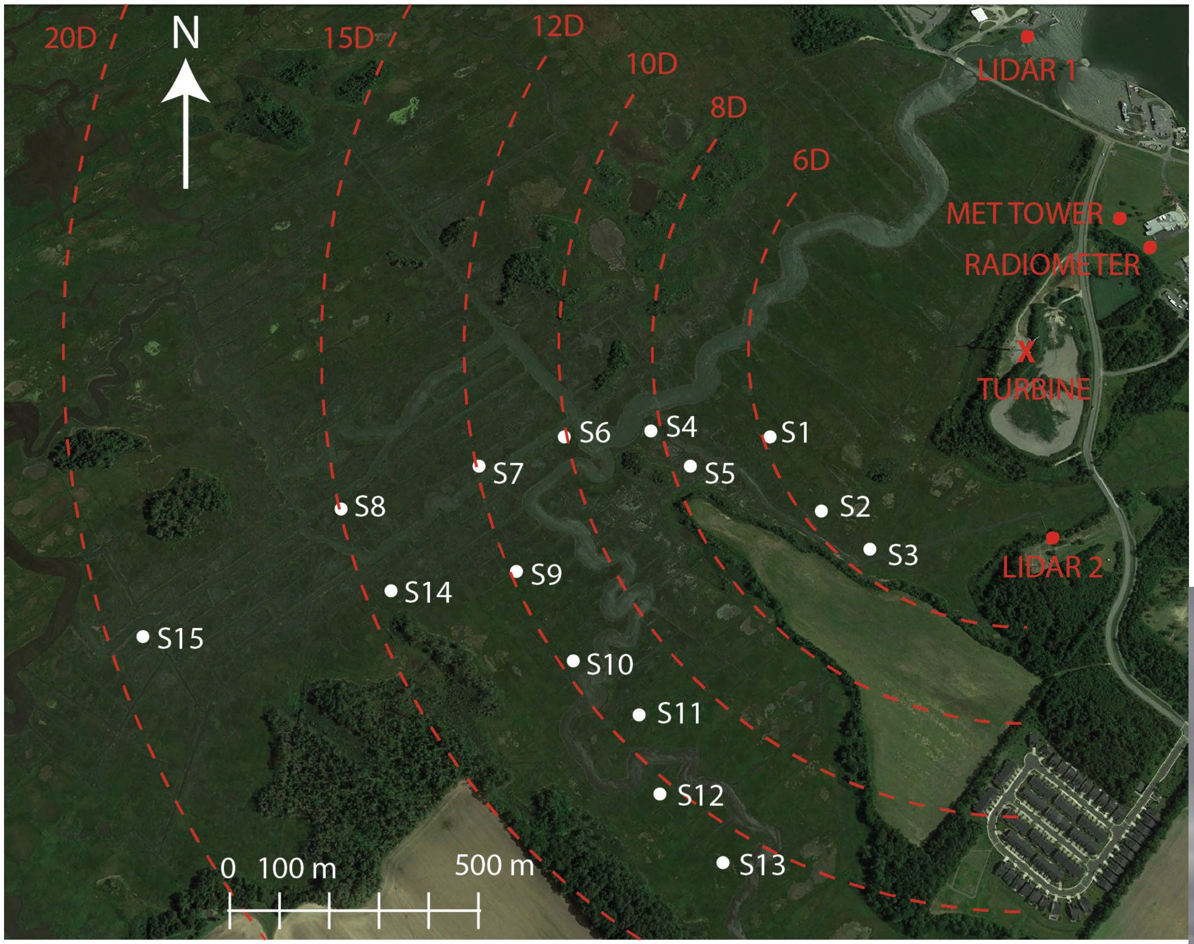
The VERTical Enhanced miXing (VERTEX) field campaign in Lewes, DE

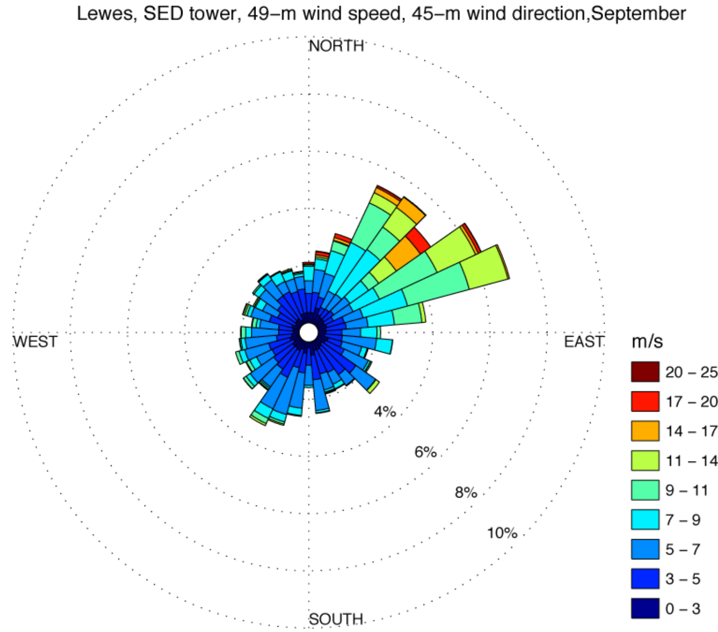


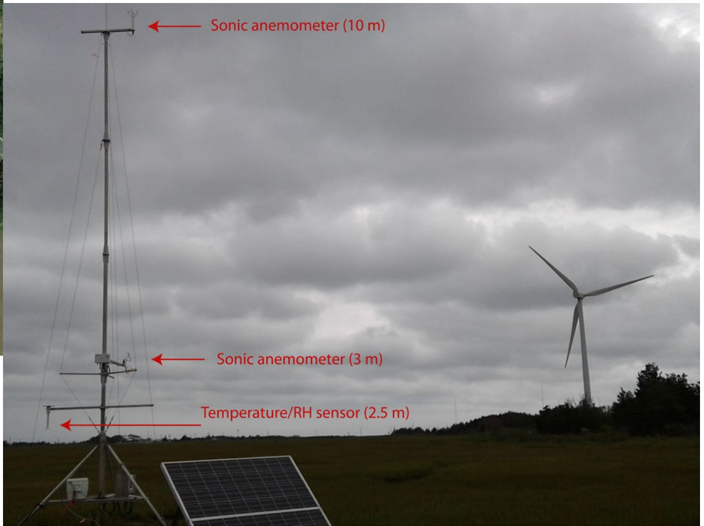


http://www.ceoe.udel.edu/lewesturbine/index.shtml

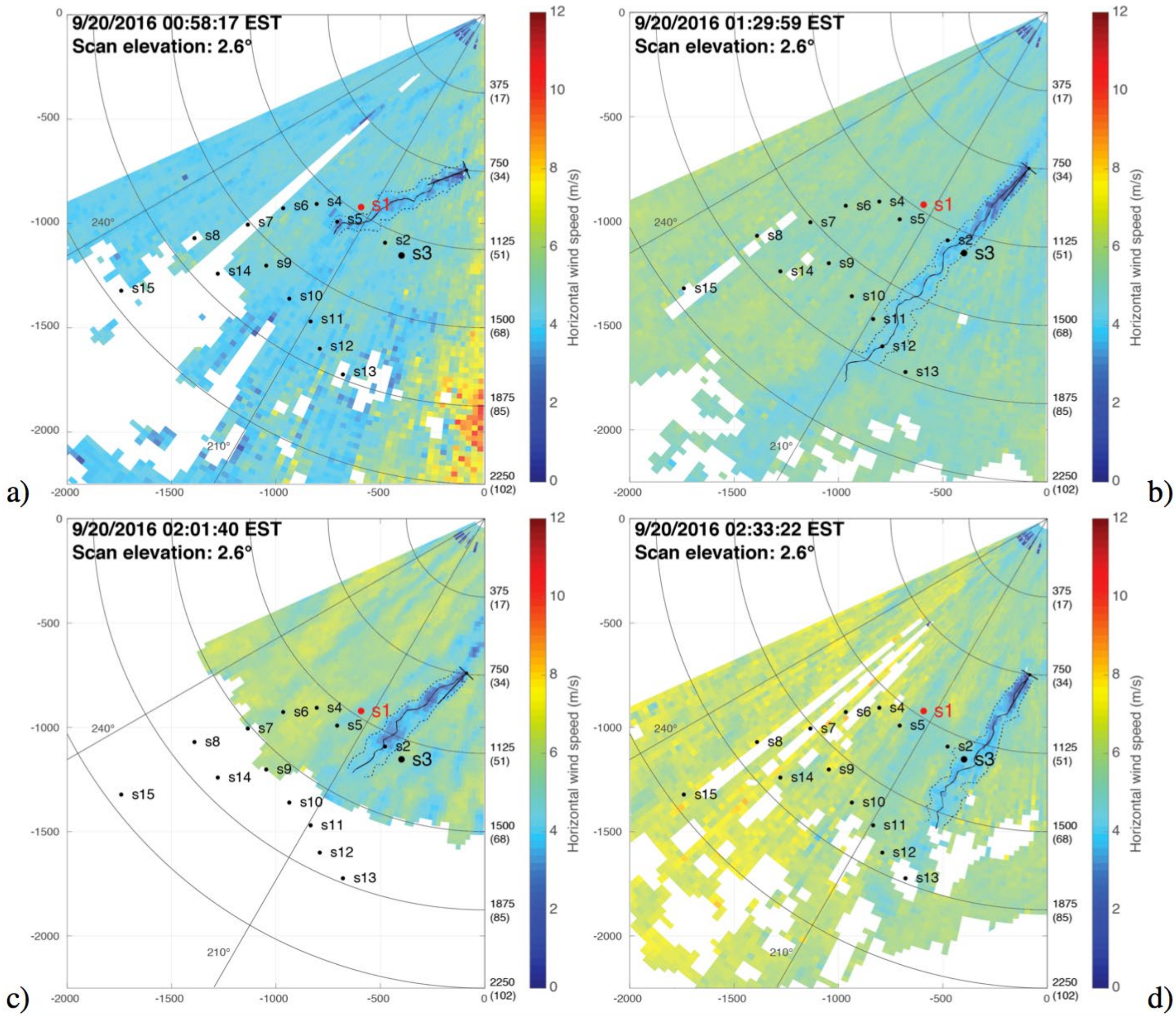
Layout of the VERTEX campaign





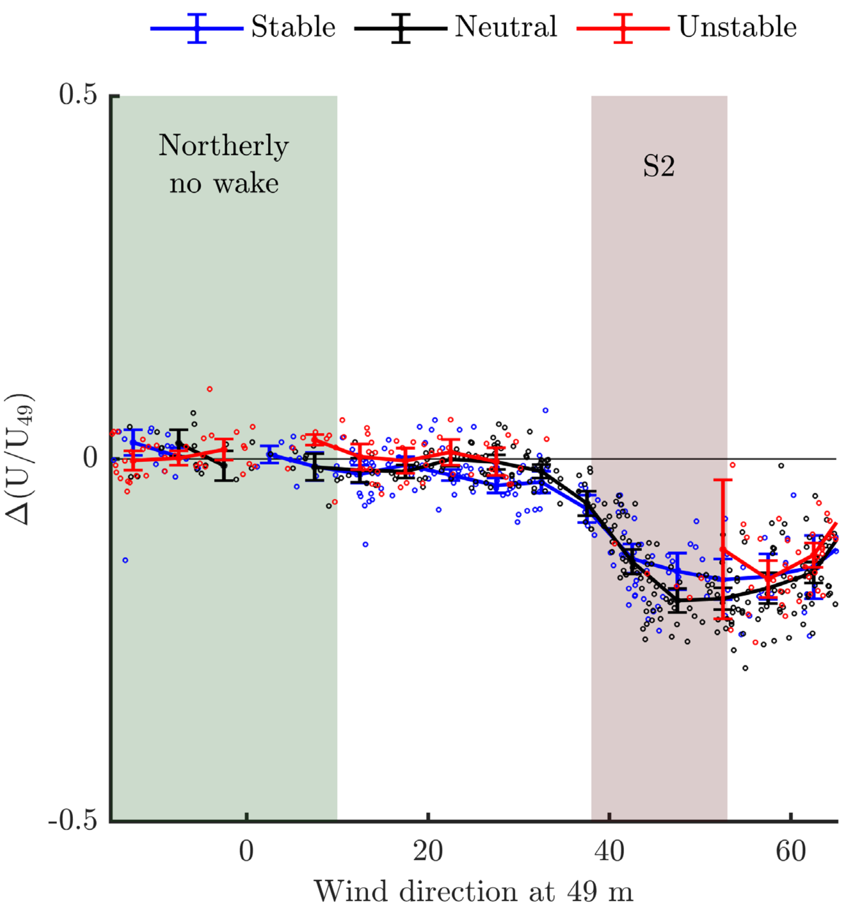


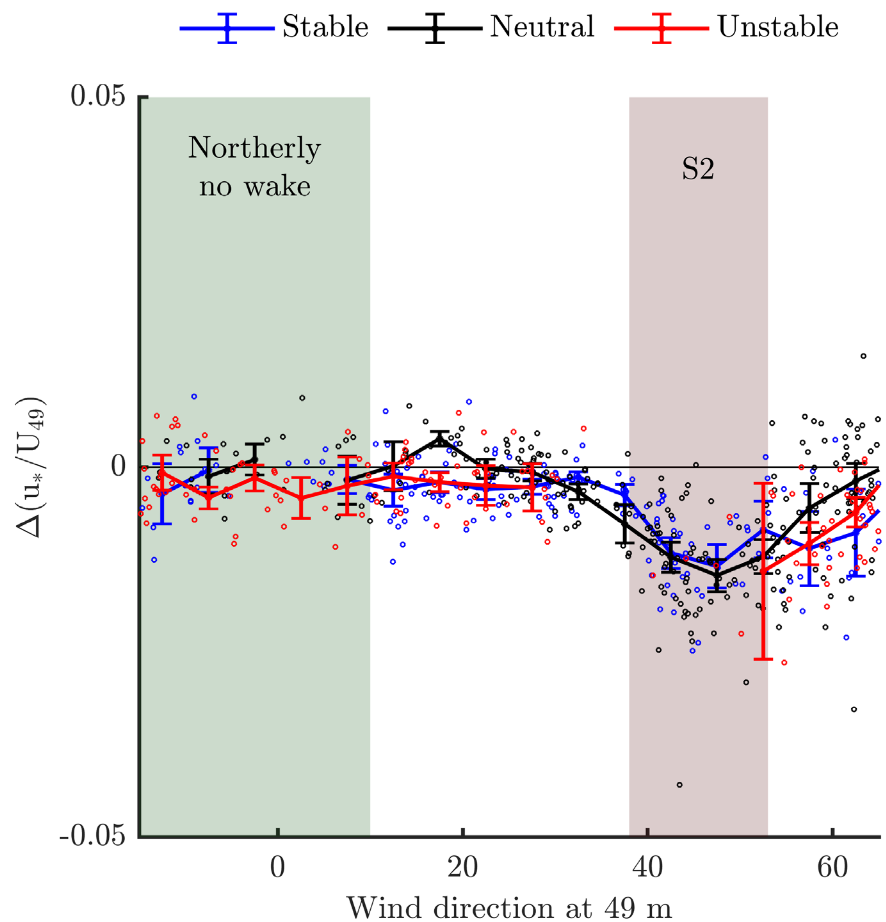
Neutral case: 20 September 2016



Archer et al., JoT 2019

All cases: Wind speed and u_* are reduced under the wake





Wu and Archer, MWR 2021

Summary of VERTEX findings

$\Delta(U/U_{49})$		S2-S1	S3-S1	S10-S7
No-wake conditions	Stable	0.006 (0.032)	-0.012 (0.042)	0.032 (0.039)
	Neutral	-0.001 (0.028)	-0.030 (0.043)	0.027 (0.029)
	Unstable	0.003 (0.026)	-0.031 (0.029)	0.031 (0.029)
Wake conditions	Stable	-0.123 (0.053)	-0.126 (0.051)	-0.125 (0.055)
	Neutral	-0.132 (0.056)	-0.128 (0.048)	-0.116 (0.052)
	Unstable	-0.156 (0.051)	-0.090 (0.037)	-0.137 (0.053)

Wu and Archer, MWR 2021

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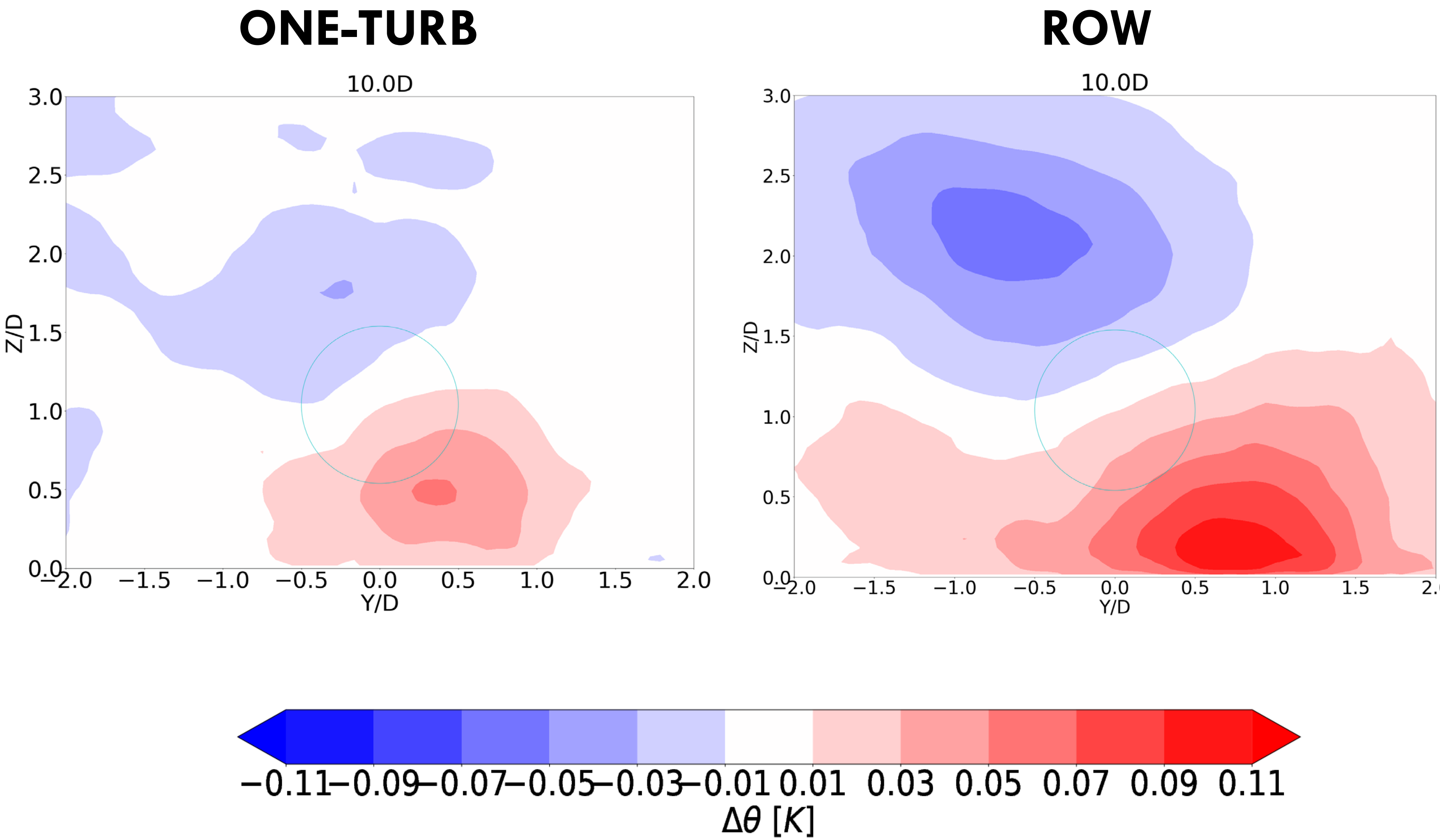
$\Delta(u^*/U_{49})$		S2-S1	S3-S1	S10-S7
No-wake conditions	Stable	-0.002 (0.004)	-0.001 (0.005)	-0.002 (0.003)
	Neutral	-0.002 (0.003)	-0.001 (0.003)	-0.002 (0.004)
	Unstable	-0.001 (0.004)	-0.001 (0.004)	-0.001 (0.004)
Wake conditions	Stable	-0.010 (0.006)	-0.008 (0.006)	-0.004 (0.007)
	Neutral	-0.010 (0.006)	-0.008 (0.005)	-0.002 (0.006)
	Unstable	-0.012 (0.007)	-0.007 (0.004)	-0.005 (0.005)

$\Delta(\overline{w'T'_v})$		S2-S1	S3-S1	S10-S7
No-wake conditions	Stable	0.000 (0.013)	-0.005 (0.013)	0.002 (0.007)
	Neutral	0.003 (0.010)	-0.002 (0.009)	0.003 (0.014)
	Unstable	-0.004 (0.016)	-0.009 (0.013)	-0.003 (0.006)
Wake conditions	Stable	-0.006 (0.006)	-0.003 (0.005)	-0.010 (0.055)
	Neutral	-0.002 (0.004)	-0.002 (0.004)	-0.005 (0.005)
	Unstable	-0.003 (0.005)	-0.007 (0.008)	-0.006 (0.013)

$\Delta(T)$		S2-S1	S3-S1	S10-S7
No-wake conditions	Stable	-0.12 (0.12)	-0.11 (0.12)	0.08 (0.15)
	Neutral	-0.11 (0.09)	-0.07 (0.07)	0.10 (0.08)
	Unstable	-0.01 (0.10)	-0.06 (0.07)	0.11 (0.11)
Wake conditions	Stable	0.09 (0.09)	0.10 (0.10)	0.19 (0.15)
	Neutral	-0.01 (0.06)	0.02 (0.06)	0.15 (0.06)
	Unstable	0.00 (0.07)	-0.07 (0.08)	0.09 (0.10)

Temperature: LES (Stable)

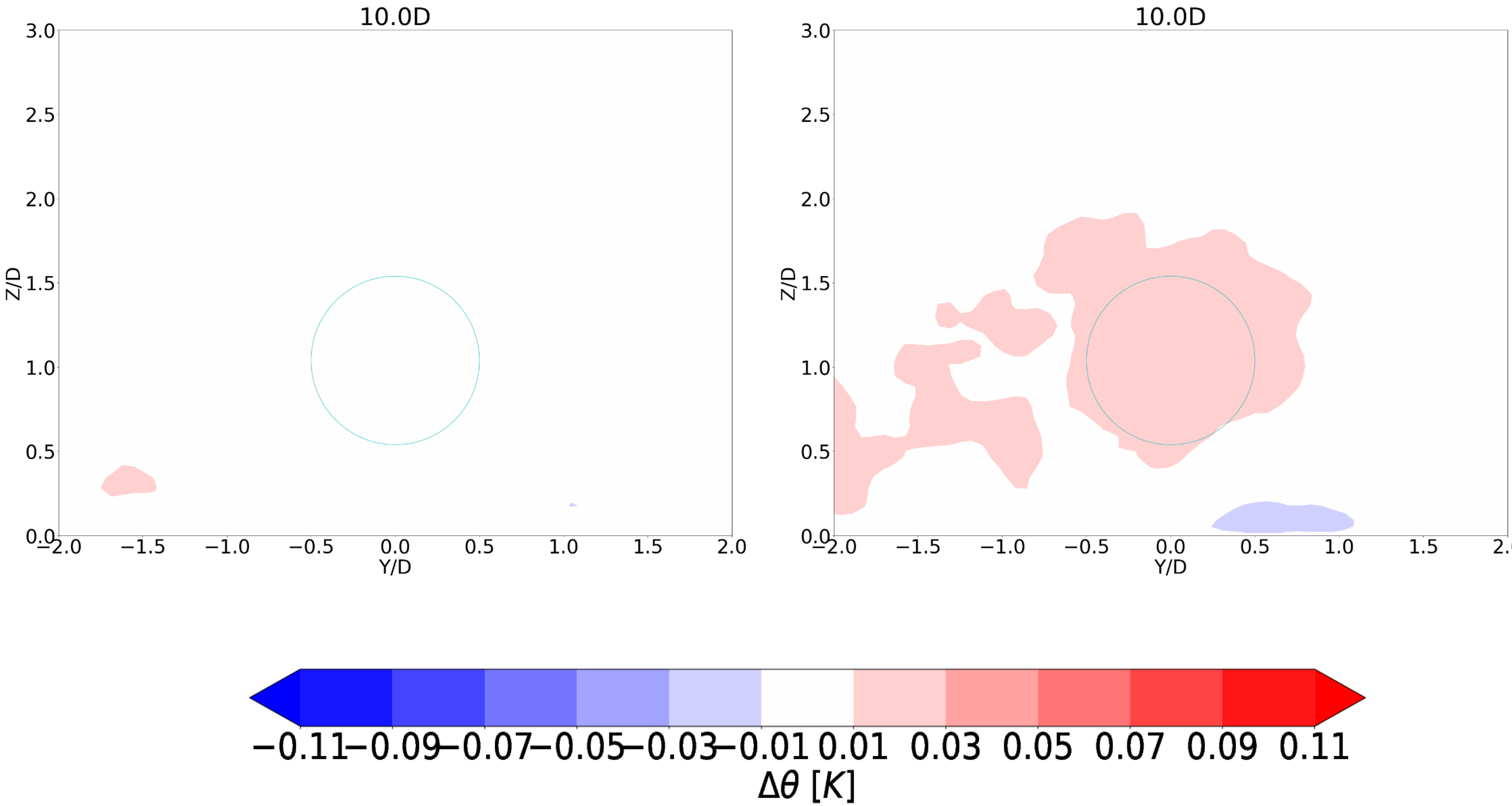


Wu et al. (2023)

Temperature: WRF-LES (Unstable)

ONE-TURB

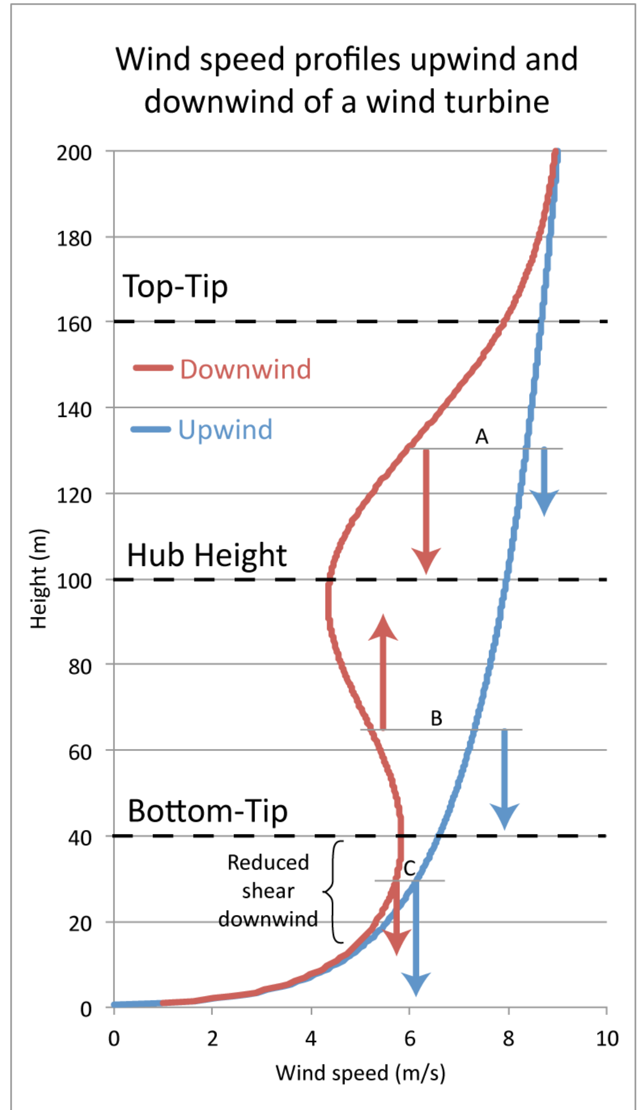
ROW



Wu et al. (2023)

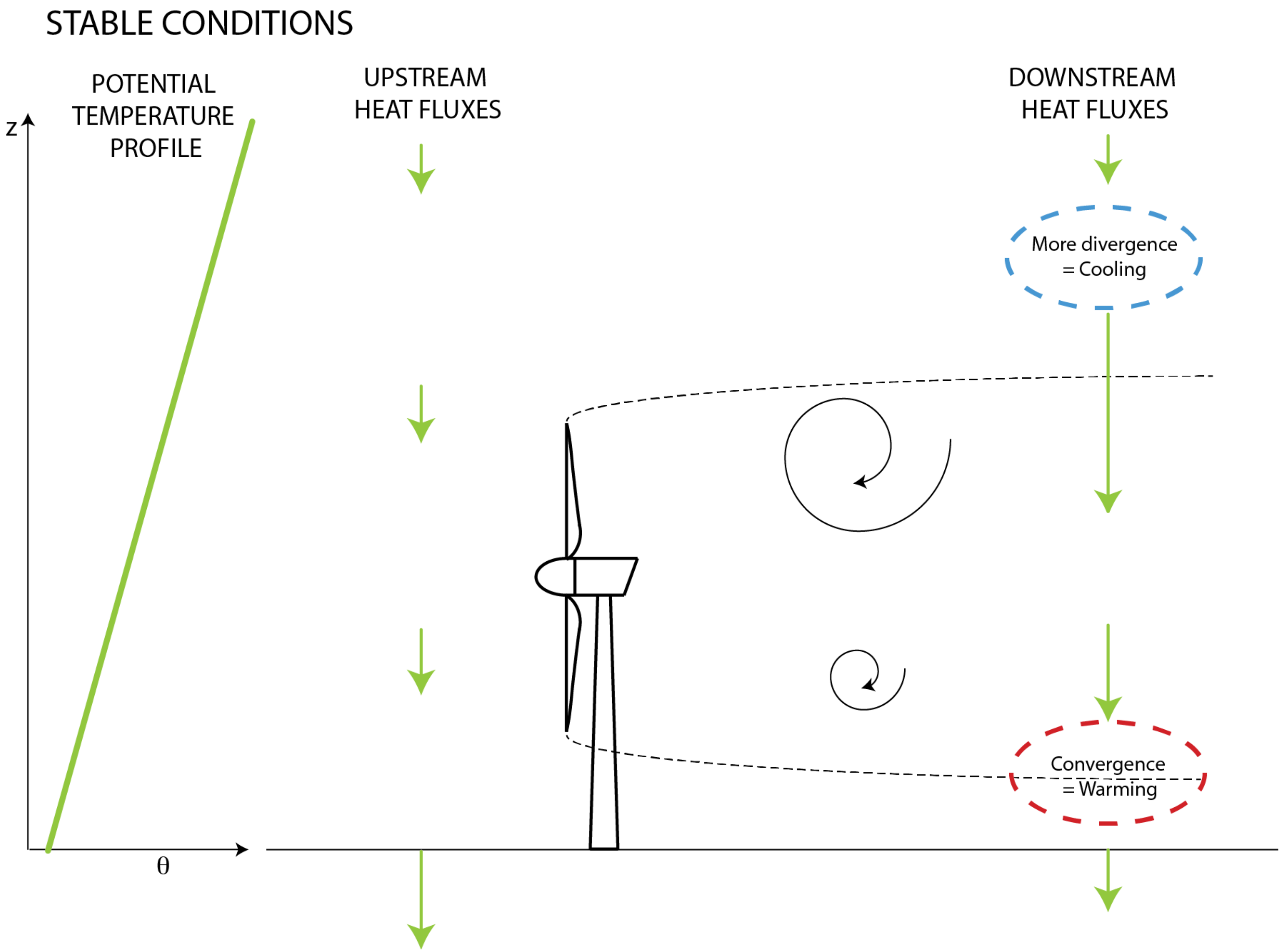
Wind turbines reduce vertical mixing and TKE near ground by reducing shear

- Wind shear below the rotor is reduced;
- Vertical momentum flux (arrows) is reduced (point C);
- Production of TKE is reduced;
- Vertical mixing is reduced or unchanged.



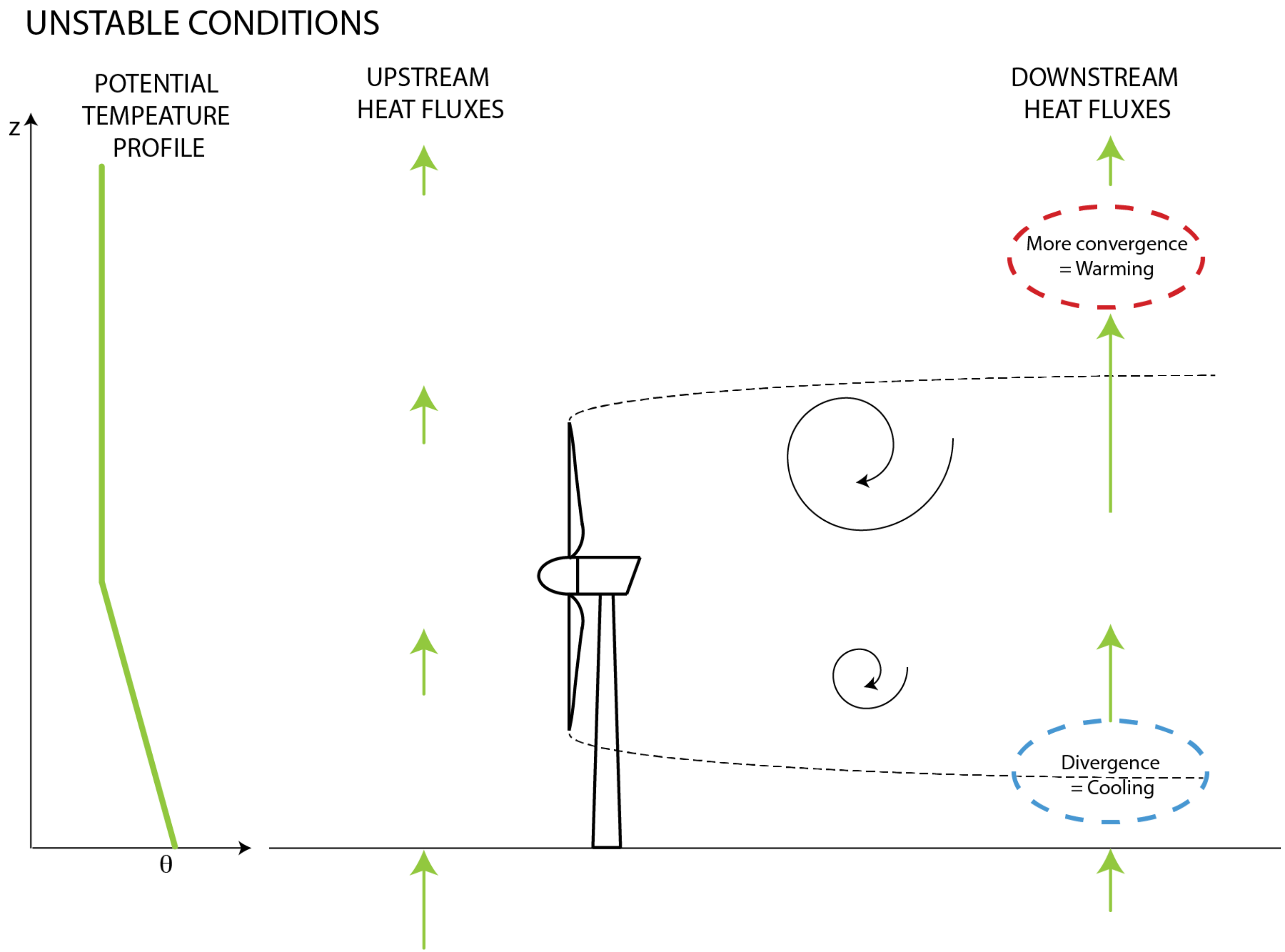
<u>What causes the warming?</u>

Heat flux divergence – Stable case



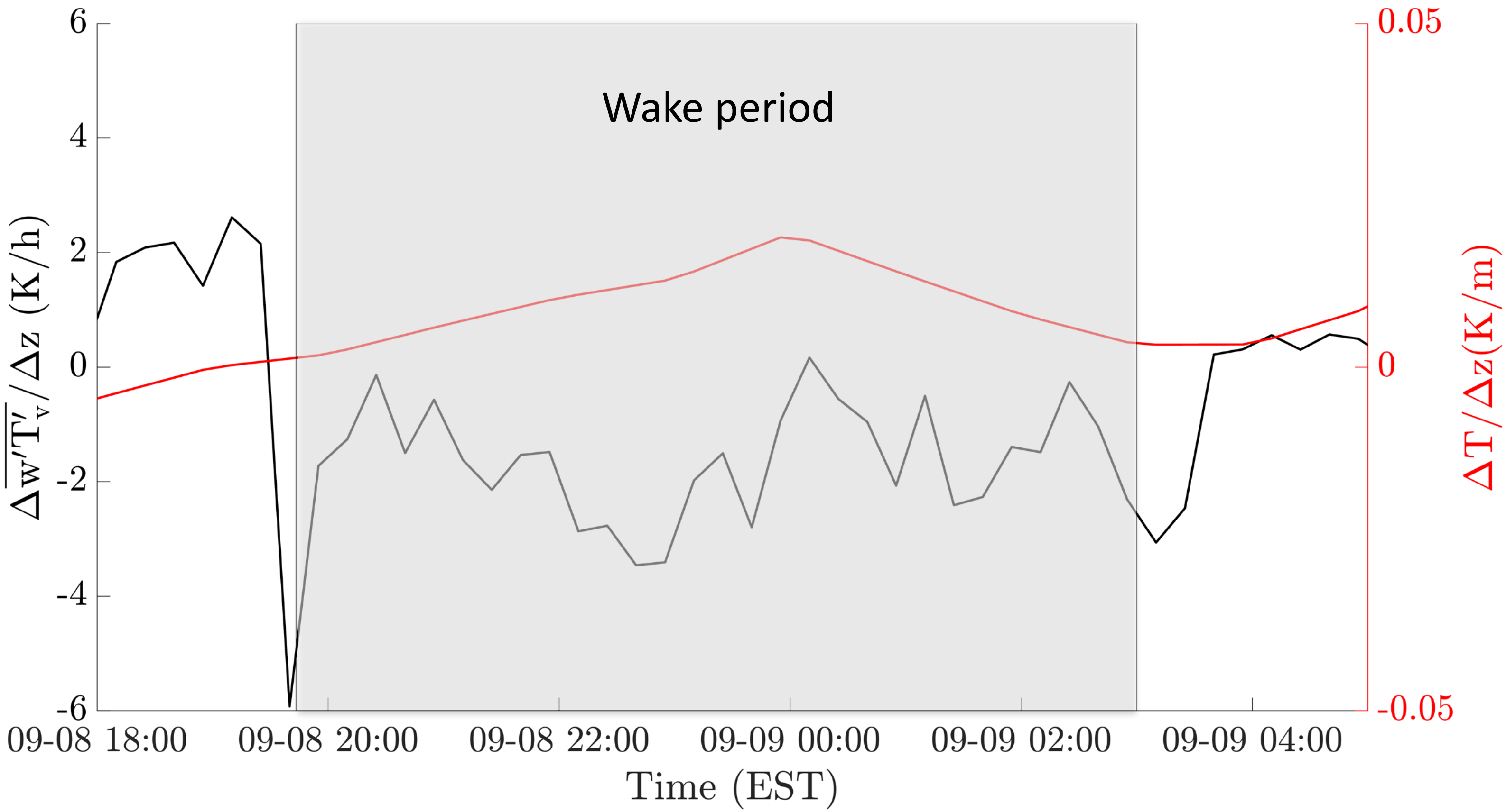
Wu and Archer (2021)

Heat flux divergence – Unstable case



Wu and Archer (2021)

Heat flux divergence – VERTEX



Wu and Archer (2021)

Energy budget equation

$$\partial_t \bar{\theta} = -\overline{U_j}\partial_j\bar{\theta} - \partial_j\overline{u_j{}'\theta'}$$

Advection Convergence

$$ADVx = -\frac{\bar{U}\frac{\partial\bar{\theta}}{\partial x}}{q_3/D}$$

$$ADVy = -\frac{\bar{V}\frac{\partial\bar{\theta}}{\partial y}}{q_3/D}$$

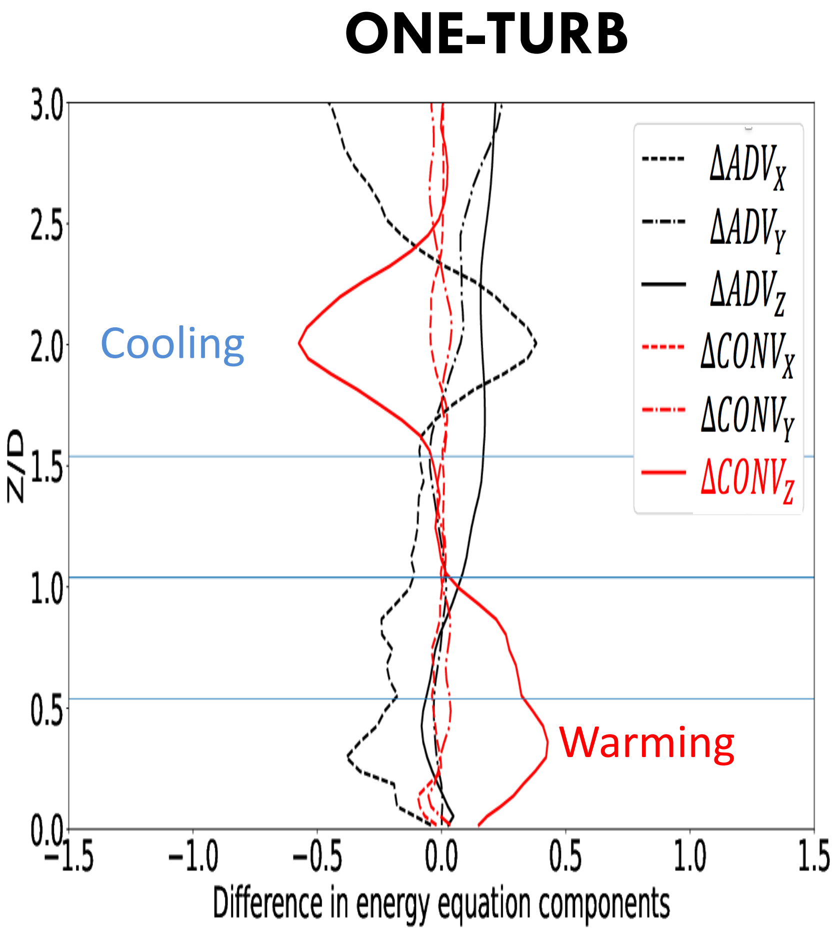
$$ADVz = -\frac{\bar{W}\frac{\partial\bar{\theta}}{\partial z}}{q_3/D}$$

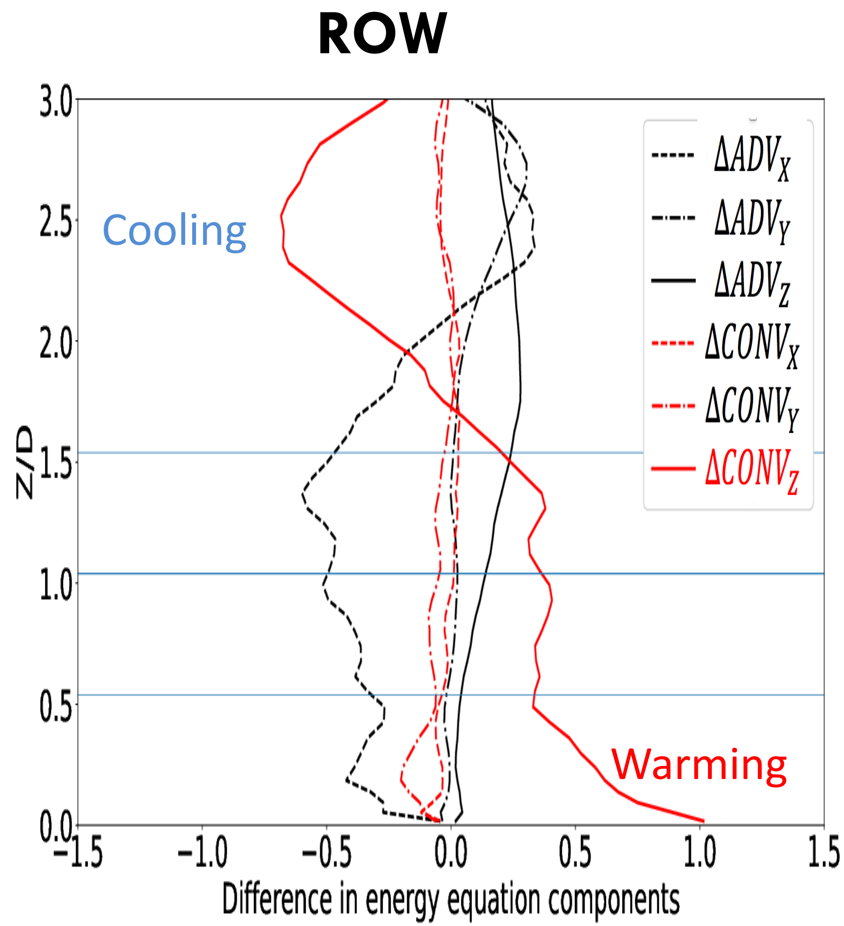
$$CONVx = -\frac{\frac{\partial\overline{u'\theta'}}{\partial x}}{q_3/D}$$

$$CONVy = -\frac{\frac{\partial\overline{v'\theta'}}{\partial y}}{q_3/D}$$

$$CONVz = -\frac{\frac{\partial\overline{w'\theta'}}{\partial z}}{q_3/D}$$

Convergence profiles - Stable

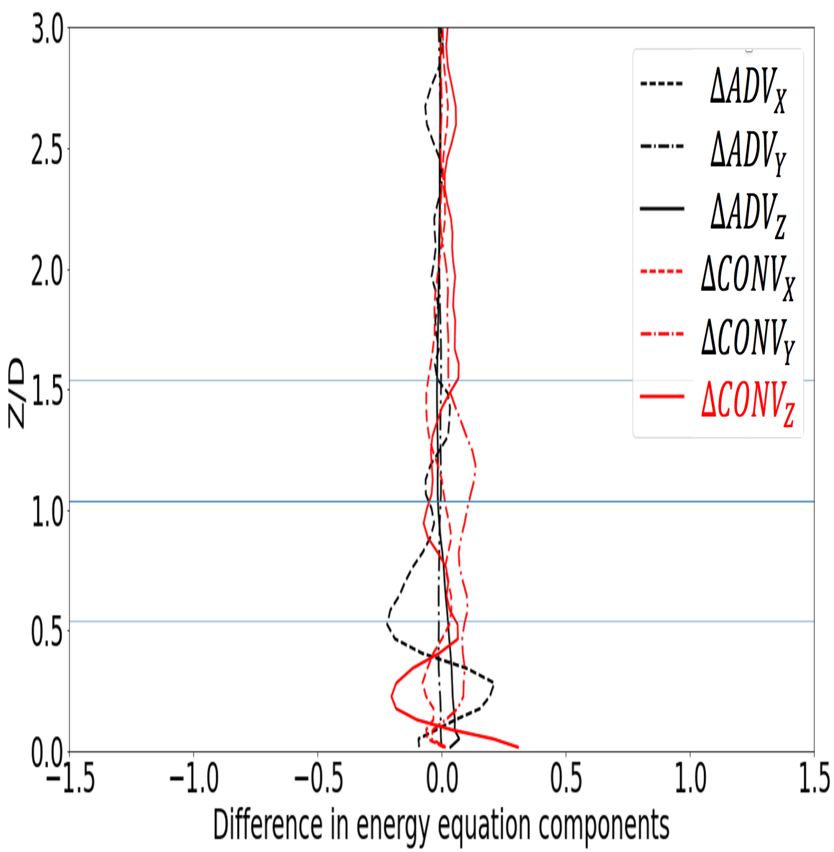




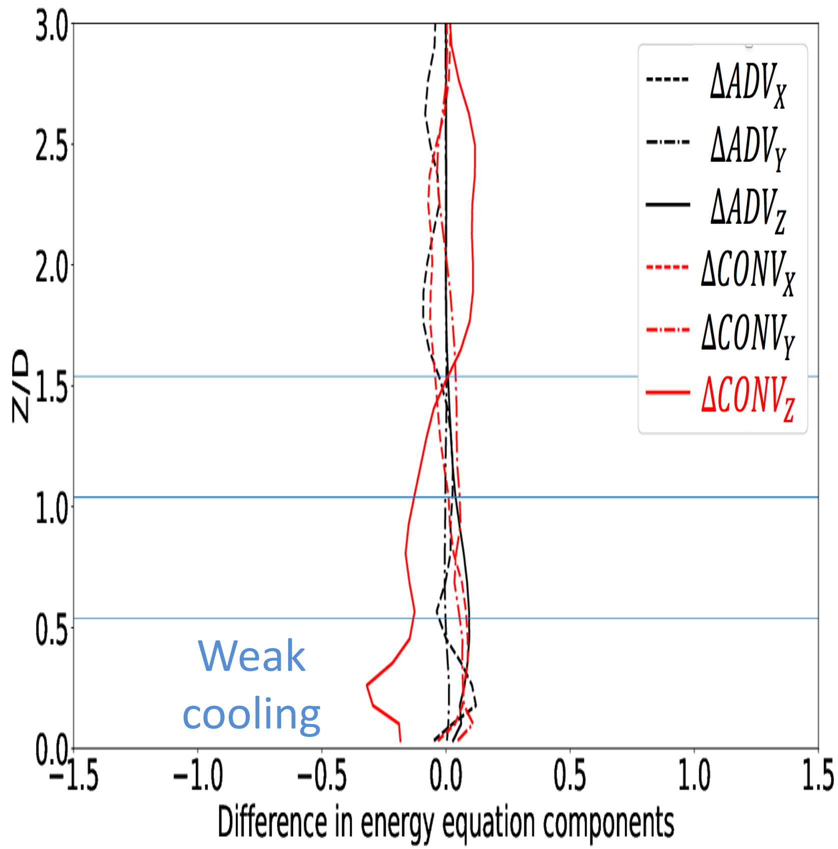
Wu et al. (2023)

Convergence profiles - Unstable

ONE-TURB



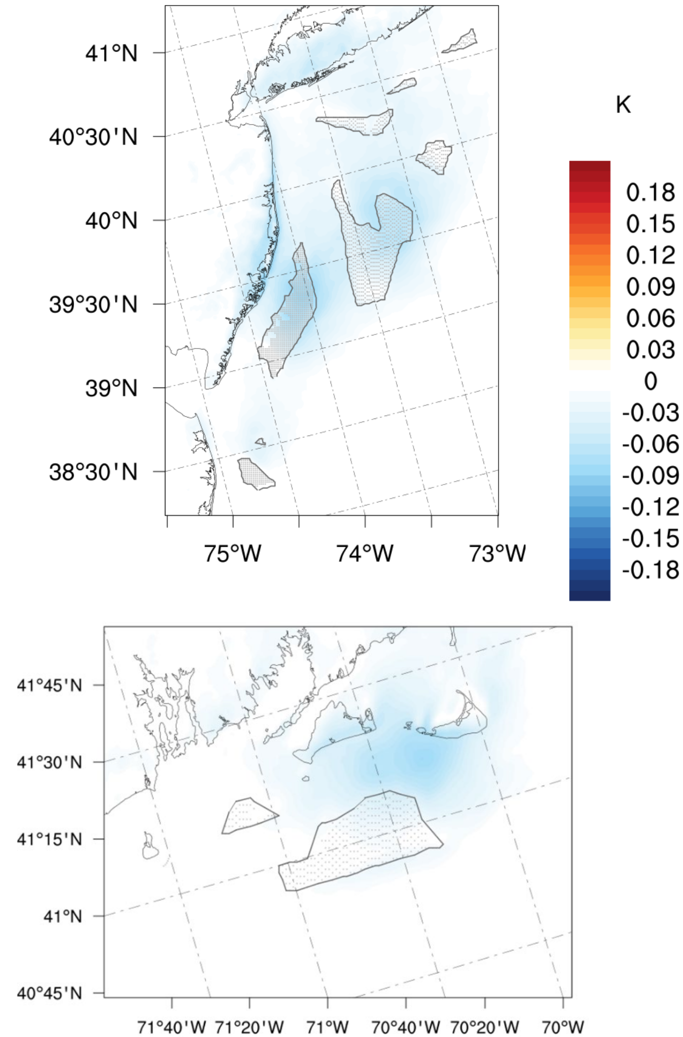
ROW



Wu et al. (2023)

Surface temperature changes

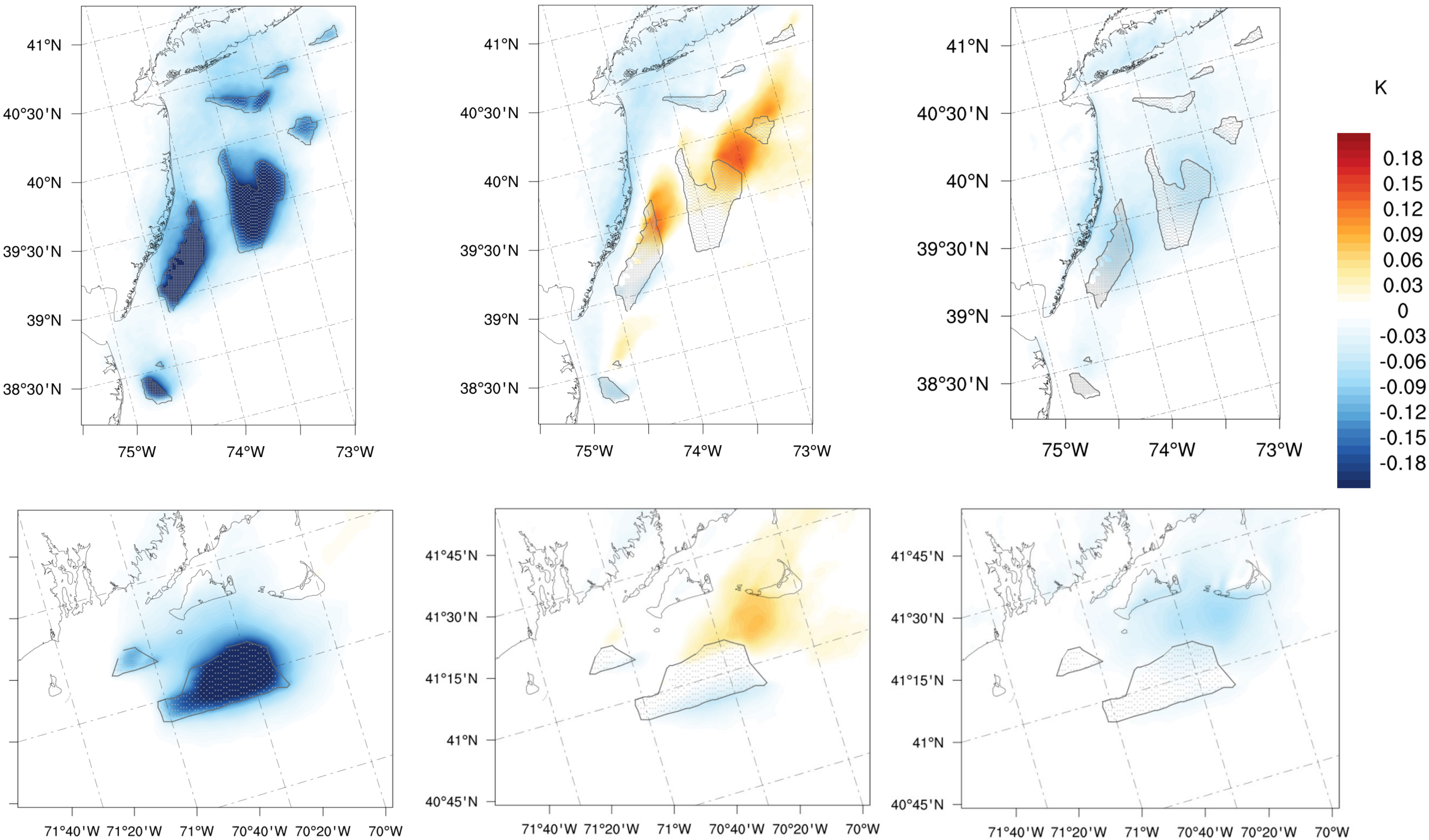
At the surface



Surface temperature changes

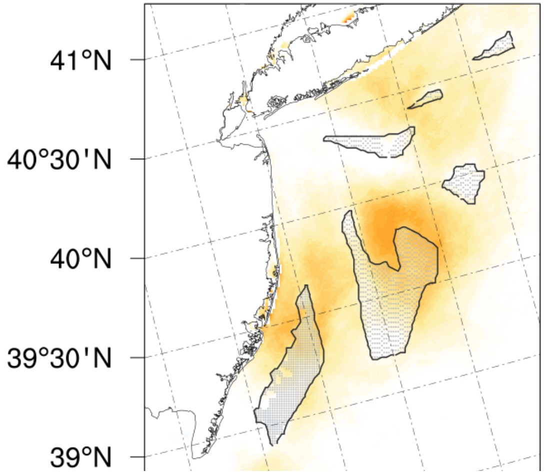
Golbazi et al., ERL 2022

Above hub height | **Below rotor** | **At the surface**

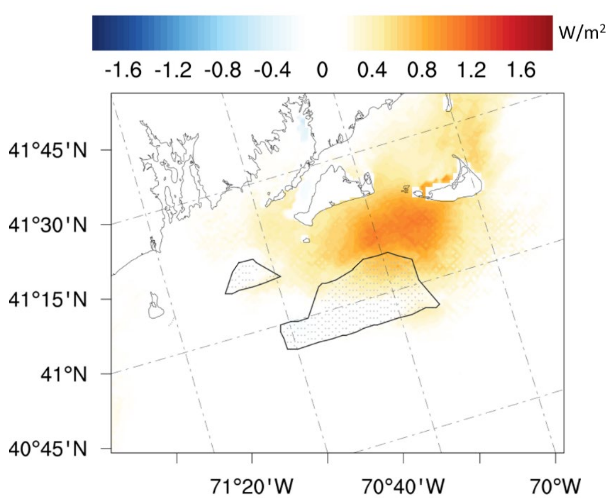


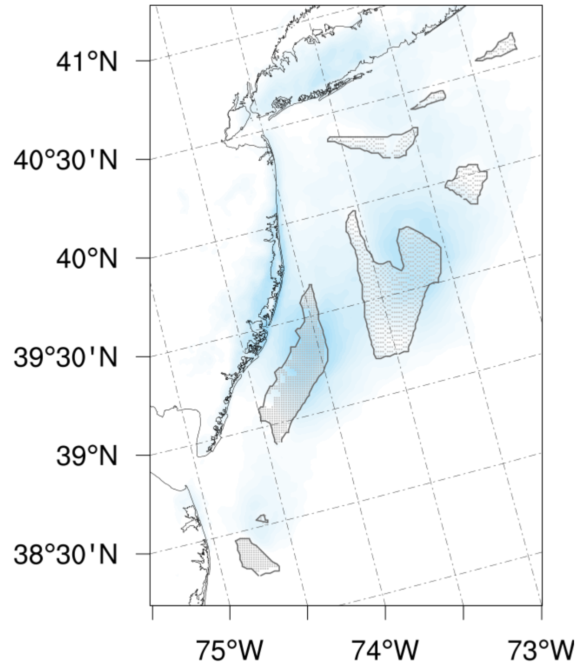
Heat flux and temperature changes

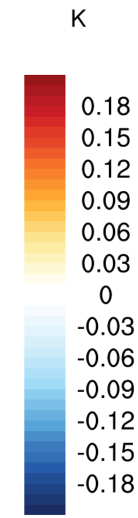
Golbazi et al., ERL 2022

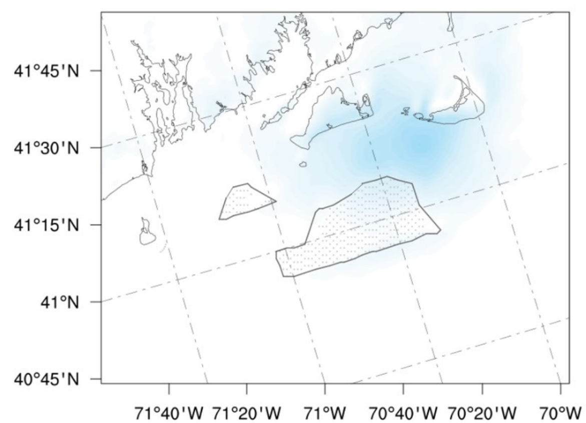


Positive change = Reduction in magnitude of downward (negative) flux



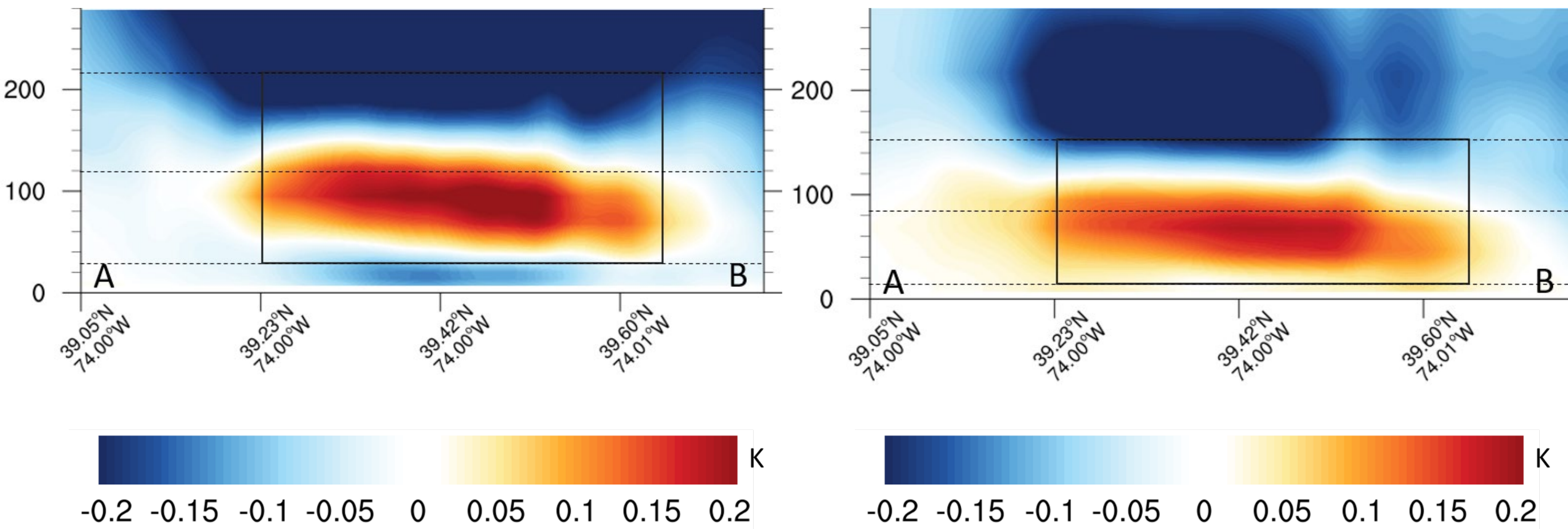






Extreme-size turbines are tall!

Extreme-size turbines (H = 120 m) | **Conventional turbines (H = 80 m)**



Golbazi et al., ERL 2022

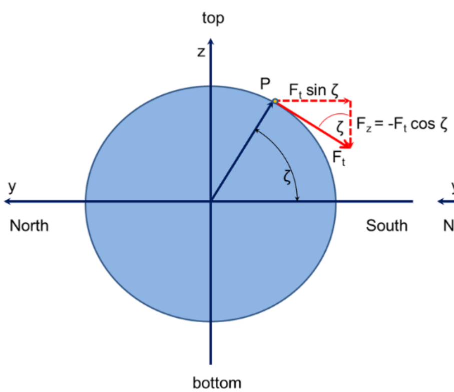
Conclusions

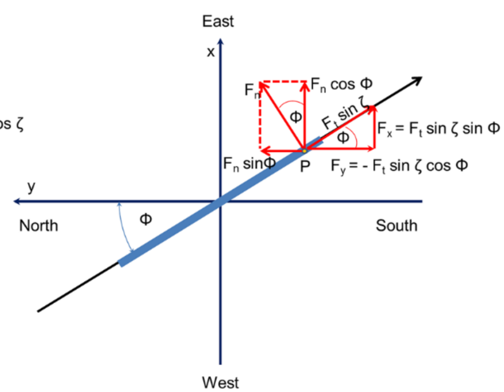
- Wake effects at the ground that occur ~always:
  - Reduced wind speed;
  - Reduced turbulence;
  - Reduced heat fluxes.
- Surface temperature effects depend on:
  - Boundary layer stability (must include rotor);
  - Divergence of heat fluxes;
  - Turbine hub height.

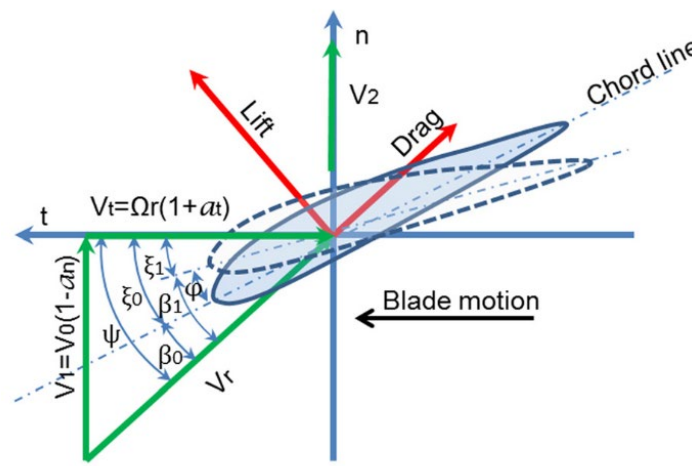
WRF-LES

- **Part of the Weather Research and Forecasting (WRF) model**
  - Widely used weather forcasting model
  - Full compressible Navier-Stokes equation using finite differencing

- **Wind turbine modeled as a Generalized Actuator Disk (Mirocha et al. 2014)**







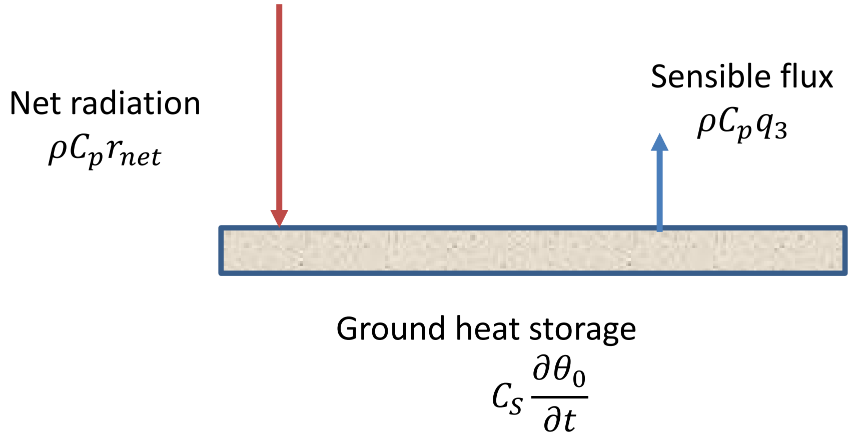
Simplified land-surface model

Bottom temperature: single layer slab surface model

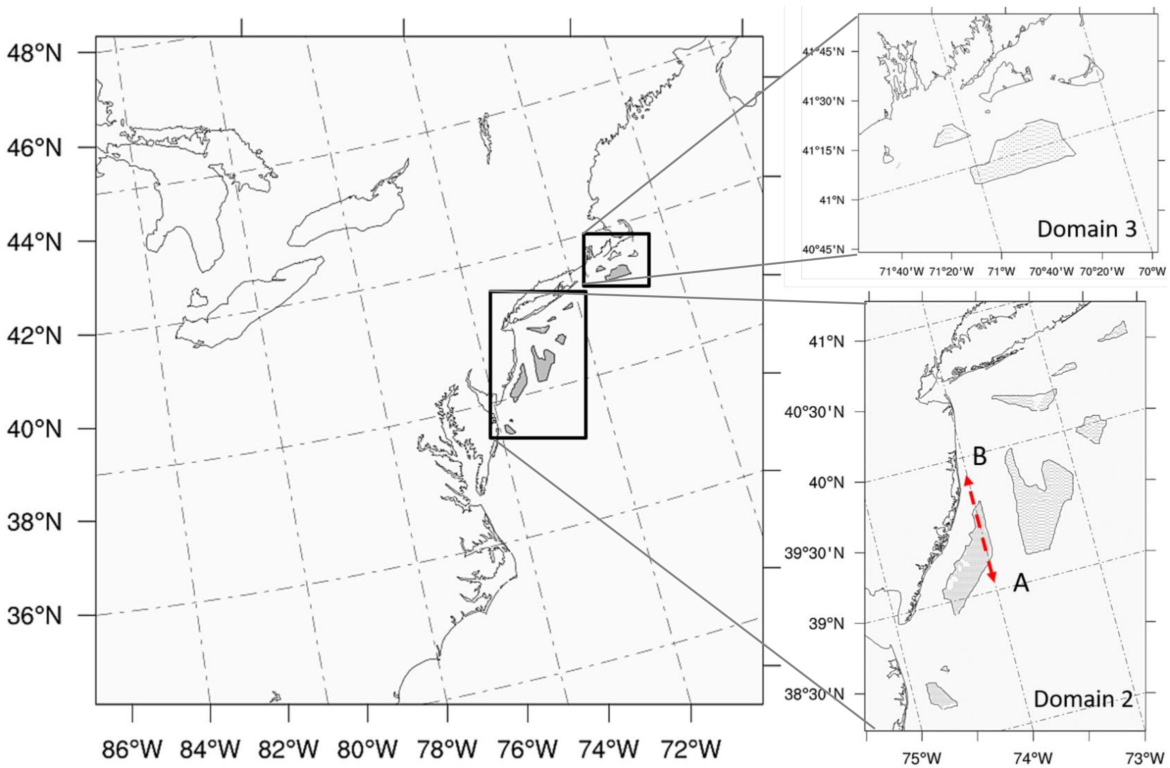
$$C_S \frac{\partial \theta_0}{\partial t} + \rho C_p (r_{net} - q_3) = 0$$

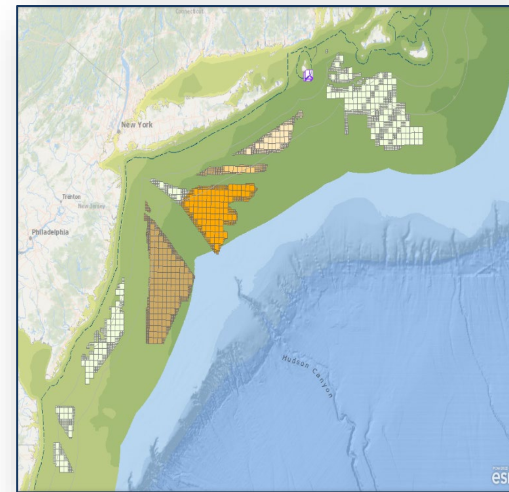
- C_S Equivalent soil heat capacity per unit area, estimated from VERTEX field campaign data $(1.6 \times 10^6 \, J \, K^{-1} \, m^{-2})$
- θ_0 Ground temperature
- ρC_p Heat capacity of air
- r_{net} Constant net radiation

$$q_3 = \frac{u_* \kappa (\theta_{SK} - \tilde{\theta})}{ln(\frac{Z}{Z_0}) - \Psi_H}$$



30 GW of offshore wind by 2030





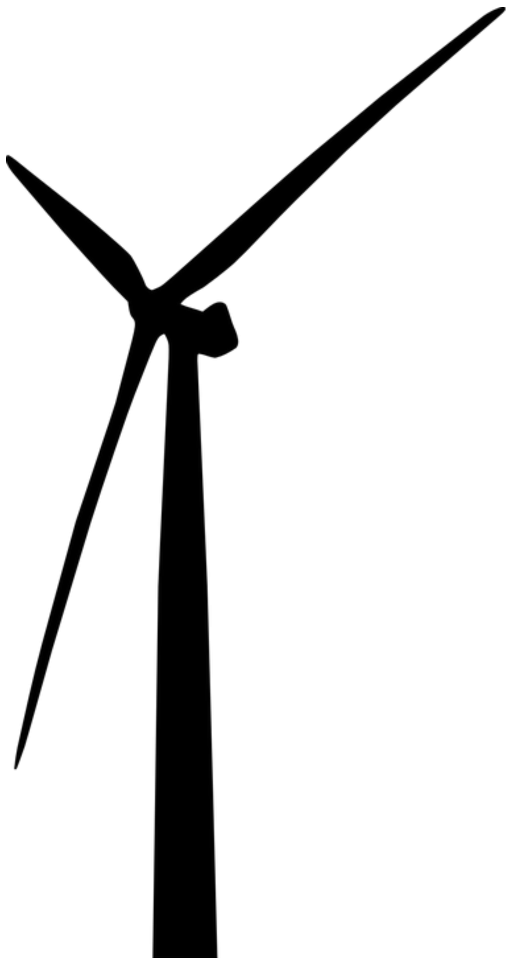
WRF simulations with Fitch

Domain	Characteristics	
Parent Domain	400 x 400	4 km
Domain 2: NJ & NY & MD & DE	260 x 170	1.3 km
Domain 3: MA, RI, CT	132 x 105	1.3 km

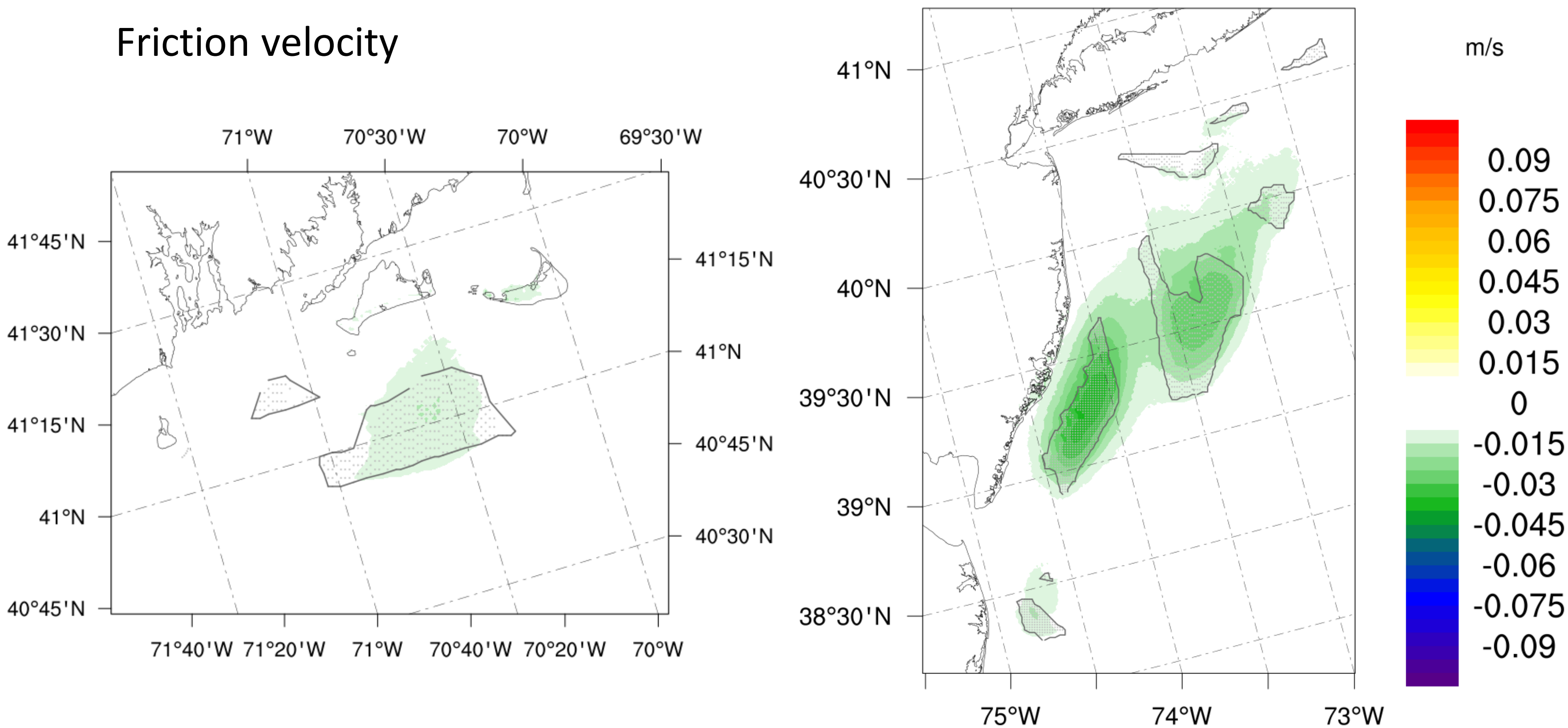
Golbazi et al., ERL 2022 (under review)

Extreme-size wind turbines

Parameter	Value
Rating	10 MW
Rotor diameter	178.3 m
Hub height	119 m
Cut-in, Rated, Cut-out wind speeds	4 m/s, 11.4 m/s, 25 m/s

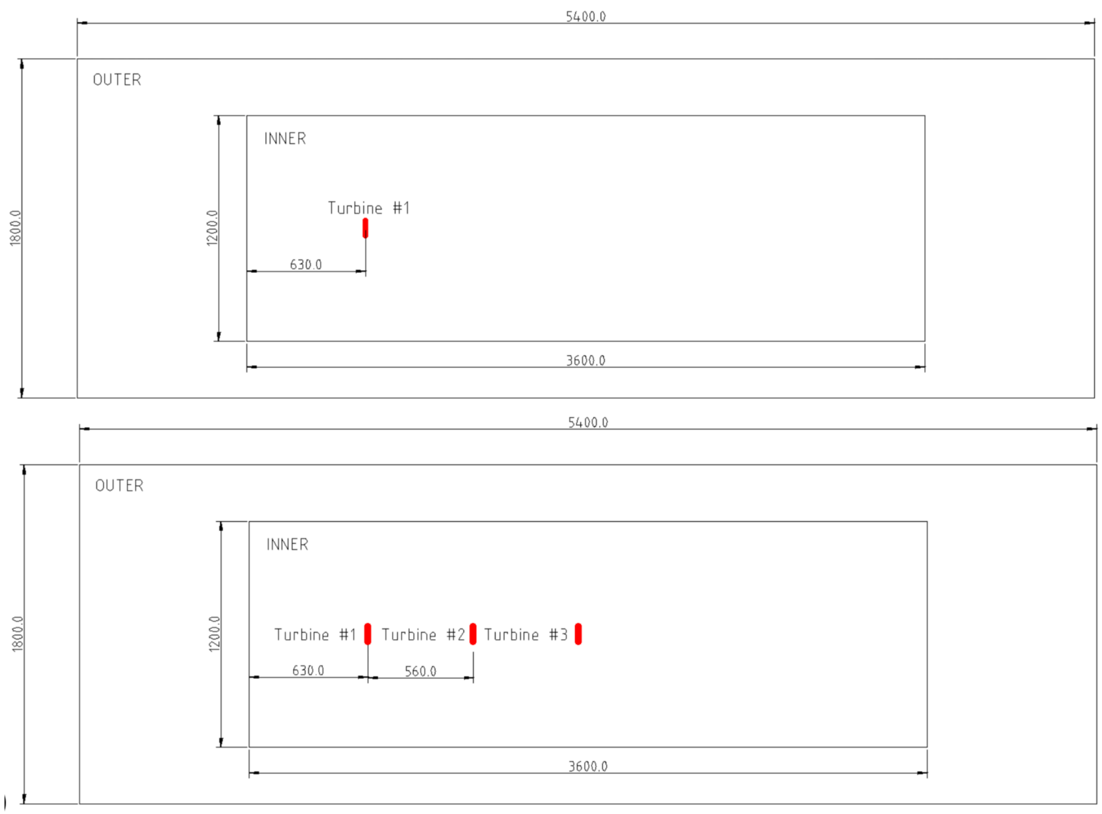


Friction velocity



Wind speed is decreased at the surface. It influences the surface friction and decreases the friction velocity.

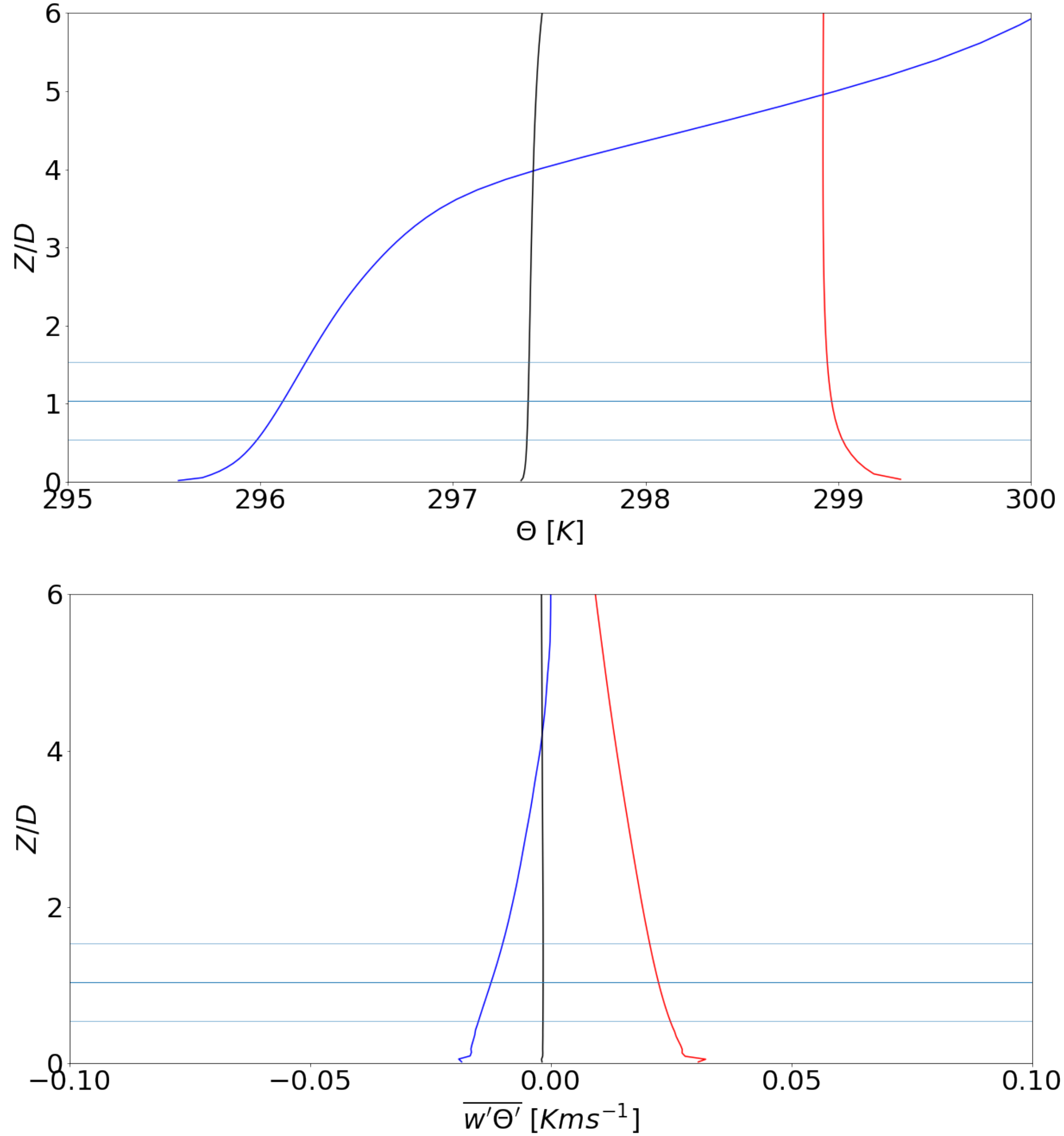
WRF-LES setup



- Turbine (actuator model):
  - PSU 1.5 MW;
  - Hub 80 m;
  - Diameter 77 m.
- One-way nested domain
  - Outer domain: 5400 m x 1800 m (@15 m, periodic);
  - Inner domain: 3600 m x 1200 m (@5 m, nested).
- Domain height depends on stability.
- Three configurations, three stabilities each:
  - **NO-TURB** (no turbines);
  - **ONE-TURB** (one turbine);
  - **ROW** (three turbines).

Wu and Archer, MWR 2022 (under review)

Profiles without turbines (NO-TURB)



Wu and Archer, MWR 2022